

IBM

Technical Directions

Federal Systems Division

Fall/Winter 1981 Vol. 7 No. 3



Ground Control Systems and Stations for Satellites and Space Shuttle

On the Cover . . .

Two critical elements of future DoD space operations, the Space Shuttle and Launch Processing System, are depicted. Articles in this issue address IBM's role in ground control systems for space missions.



Technical Directions

Federal Systems Division

Fall/Winter 1981

Vol. 7 No. 3

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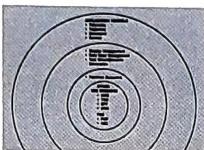
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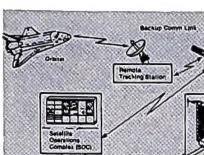
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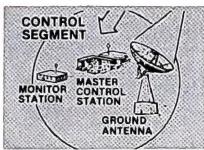
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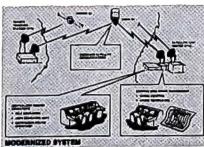
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Commonality of Real-Time Command and Control

by George A. Gaxiola

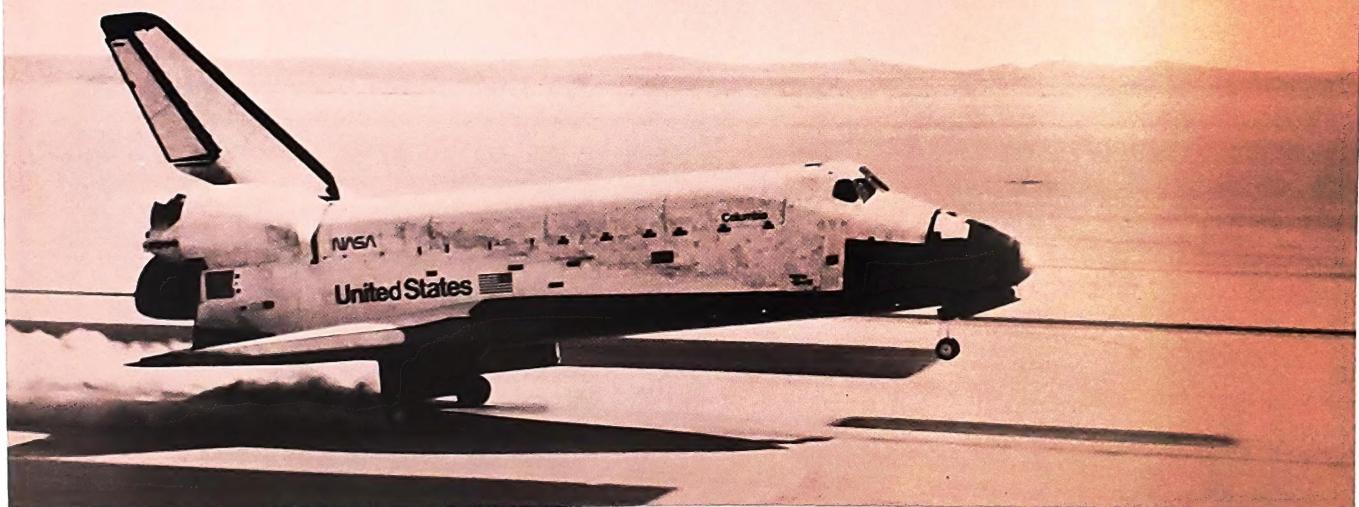


Figure 1. The Space Shuttle Columbia returns November 14 to Edwards Air Force Base from its historic second space mission.

The United States defense forces over the past 20 years have increasingly relied on space satellite systems to support the command and control functions for worldwide communications, navigation and location, weather data gathering and handling, and surveillance and warning missions.

IBM's Federal Systems Division (FSD) has been assisting in the development of the growing numbers of ground systems to support these space missions,

including launching and monitoring of satellites. In the future, FSD will be supporting DoD Space Shuttle (Figure 1) and its payload operations.

The amount of data processing required to support the mission objectives, keep the satellites healthy, and provide mission data to military units has increased dramatically in those twenty years. During crises and conflicts, such as Vietnam, involving worldwide defenses, data processing

has improved the acquisition of data from satellites, the interpretation of satellite observed events and the summary presentation and distribution of events to military forces.

General Future Requirements

Space makes an ideal platform for observing what is happening on and near the earth's surface, from detection of nuclear explosions to the report of a

missile or satellite launch. The detection of these events improve the monitoring of treaties and ballistic missile early warning alerts. Initially, processing of spaceborne observations was done on the ground in a batch processing system; hours were required to process and analyze a few scans of data before reporting to the military commands. Currently some of the processing is done in real time on systems with reports to the military commands within minutes of the event's occurrence. Numerous systems are using interactive non-real-time processing.

In the future, the increase in mission capability provided by the more sophisticated satellite missions and the increased launch size of satellites will provide more information for the assessment and direction of the global and local military situation. New data processing techniques must be developed to interpret the data, fuse the data streams and summarize the information content for the user. The information is needed much faster today for the direction of crises and conflict responses to provide adequate time to assimilate the data and review alternate courses of action. Increases of performance in the real-time data processing systems are key to the planned implementation of this approach. Significant amounts of similarity exists between these programs giving rise to the potential of using common hardware and software across multiple projects.

The Near Term

During the 1980s and beyond, the United States space program will have a number of mission control centers being upgraded or built under the auspices of DoD and the National Aeronautics and Space Administration (NASA).

Those under DoD will include:

- The Air Force's Satellite Control Facility (SCF)—currently being upgraded by the IBM Federal Systems Division (FSD) under the Data System Modernization (DSM) project.
- The Master Control Station for the Global Positioning System (GPS)—currently under development by FSD
- The Shuttle Operations and Planning Complex (SOPC)—being studied by FSD as the mission control center for military shuttle missions

- The Space Defense Operations Center (SPADOC),—providing centralized command and communications for defense purposes.
 - The Consolidated Space Operations Center (CSOC)—scheduled to provide a centralized facility for military space operations.
- Mission control centers under NASA are located at:
- The Lyndon B. Johnson Spacecraft Center (JSC)
 - The John F. Kennedy Spacecraft Center (KSC)
 - The Goddard Space Flight Center (GSFC)

In the past, centers have been developed essentially independently, not drawing upon each other's experience and products. Such action has resulted in some amount of risk, schedule and cost exposures that perhaps could have been avoided. However, recent studies within FSD have shown that it is highly desirable to develop these control centers so as to take advantage of common elements in both hardware and software from one center to another. In addition, it is desirable to use existing, field-proven components when possible. This commonality provides significant advantages in reducing development and life-cycle costs, improving schedules, and perhaps, most importantly, enhancing reliability and thus reducing the overall technical risk in developing highly complex real-time command and control systems.

Preliminary work on the feasibility of a commonality approach was done by FSD at its facility in Houston as part of an effort to use software from the Shuttle Ground-Based Space System (GBSS) in the Shuttle Payload Operations Control Center (POCC), each using an IBM System/370 Model 168. These efforts were advanced in Gaithersburg during the proposal phases for both the Global Positioning System, a space-based RF navigation and positioning system, and the Data System Modernization program, an upgrade for the SCF. Results of these efforts showed that IBM's 3030 and 4300 series processors provide solutions to hardware requirements, while significant amounts of existing software produced by other IBM divisions and FSD offer a large common software foundation for real-time command and control system applications.

The common software concept is shown in Figure 2. The nucleus of the diagram contains the software (over five million source lines) which is common to GBSS, DSM, and the GPS Master Control Station. This includes existing IBM products: the Multiple Virtual Storage (MVS) operating system, the Time Sharing Option (TSO), the System Productivity Facility (SPF) and the Virtual Telecommunications Access Method (VTAM). Also included in this common nucleus is existing software developed by FSD for the Shuttle Ground Based System: the Program Management Facility (PMF), a library management system used to control software during its development; and the Advanced Statistics Collector (ASC), a performance measurement tool used to fine-tune the real-time system.

Extending this nucleus of common software is the real-time executive (RTX), another GBSS-based product which adds to the standard MVS operating system those features required for a real-time processing environment. Still another layer of commonality is represented by FSD software capabilities in display management, data base management and test driver/scenario generation. The final layer of software commonality is represented by kernels of software in the applications which are typical of space-oriented real-time command and control systems—telemetry, trajectory, command and control.

The feasibility of a commonality approach to real-time command and control systems software was demonstrated in three related activities which used the Ground Based Shuttle System as a base. In February 1980, the GBSS programs, (over 1,600,000 source lines) were transported from NASA's mission control center in Houston (where they were developed by FSD and executed on IBM 370/168 processors) to the IBM facility at Gaithersburg, Maryland. Only minor modifications to the display hardware interfaces were required in order to successfully execute these large, complex, real-time programs in both IBM 3033 and 4341 processors under a standard MVS operating system, thereby demonstrating the upward and downward compatibility of the system. These programs were used in Gaithersburg as a base for the GPS benchmark in March 1980; for the

SOPC upward compatibility demonstration in April 1980; and for the DSM Stage 1 demonstration, in November 1980. All of these efforts were highly successful.

As a result of this work, both GPS and DSM will be using all software elements of the common nucleus, plus an enhanced version of the real-time executive and new display software. Enroute to this achievement, major difficulties were overcome, including the establishment of a common programming language and a common set of programming standards for both the

DSM and GPS projects.

Further development of this concept is being pursued by a common systems development group established by FSD in Gaithersburg. An in-house effort, the group's primary objective is to develop system-level software which can be used across multiple present and future command and control projects.

Studies convincingly show that the commonality approach makes both sound technical and business sense. Preliminary analysis of the potential for commonality in application software such as telemetry, trajectory, and

command and control has shown the possibility of establishing common application software kernels which could be used across projects. Thus, the potential exists for carrying this commonality approach beyond the system-level software into application programs. One example would be the orbit and trajectory software required by the various systems.

The commonality approach is a concept that has matured within FSD and is currently in practice, reducing cost and technical risk and improving software scheduling.

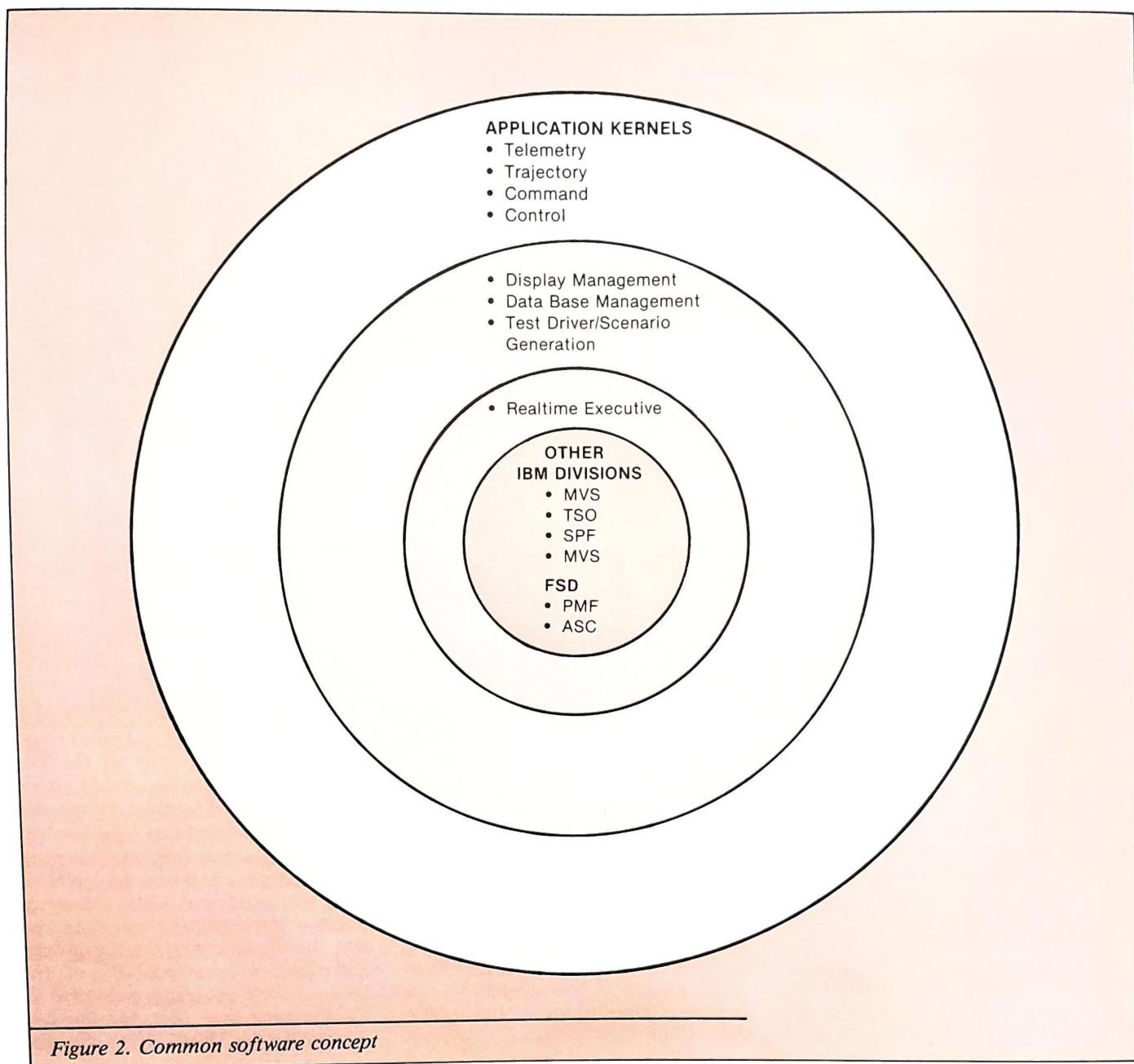


Figure 2. Common software concept

SOPC: DoD's Control Center for Space Shuttle

by Merritt E. Jones

The United States Air Force space program in the mid-1980s and beyond will utilize NASA's Space Shuttle Vehicle. The current AF facility, the Satellite Test Center (STC) at Sunnyvale, California, is for control and monitoring of unmanned vehicles and satellites and will continue in that role. The STC has previously utilized unmanned, expendable launch vehicles to conduct space operations. The advent of the manned, reusable Space Shuttle launch vehicle for AF use requires a new DoD capability to function in a secure, controlled environment. This capability to plan and launch DoD missions will initially be provided at NASA's Johnson Space Center (JSC) in an environment known as Controlled Mode.

Controlled Mode

Controlled Mode is the term used to describe the changes required at JSC to provide the secure operational environment necessary to support DoD missions. These changes involve hardware, software, facilities, procedures and personnel. Modifications have been in progress since 1980 and JSC will be ready to support a DoD flight by mid-1983.

In 1979, the Office of Management and Budget Alternatives Study concluded that while Controlled Mode was satisfactory for early DoD flight operations, the stringent requirements based on Revision 8 of the DoD mission model could not be permanently accommodated by Controlled Mode. In addition, a permanent JSC solution precluded DoD mission authority, limited DoD mission flexibility, did not enhance system survivability, and did not provide the necessary levels of security. A separate DoD operated facility, to be known as the Shuttle Operations and

Planning Complex (SOPC), represented a distinctly better option.

The study considered co-locating or integrating SOPC with Vandenberg Air Force Base, JSC, STC or the proposed Satellite Operations Complex (SOC). Co-location means that the physical facilities are shared but data systems are not. Integration includes the sharing of the data systems as well as the physical plant and associated services. The study further concluded that the co-location of SOPC with SOC appeared to be economically and operationally advantageous.

SOC is the proposed backup and load sharing facility for STC and is an option to the STC upgrade, Data Systems Modernization, which is currently being performed by IBM. (See article on page 43.) The current plans are that SOC and SOPC will be co-located at a Colorado Springs facility designated the Consolidated Space Operations Center (CSOC). The Initial Operational Capability date for CSOC and SOPC is mid-1987.

Shuttle Operations and Planning Complex (SOPC) Functions

SOPC is planned to be an upward compatible version of the Shuttle planning, readiness and operations facilities at JSC. "Upward compatible" refers to a concept whereby the software is transferred from JSC but the hardware is upgraded to modern technology whenever possible. In other words, SOPC will be a functional equivalent but not a duplication of specified parts of JSC. Software impact, data security and operational concepts will be significant factors in determining the degree of duplication.

In support of NASA Shuttle opera-

tions, JSC performs 21 flight operations functions. For DoD Shuttle operations, a designated subset of those functions will be performed by SOPC and the remaining ones will be provided by other DoD capabilities such as SOC.

Figure 1 shows the distribution of the flight operations functions between SOPC and the other DoD facilities. The eleven functions performed by SOPC are Shuttle related. The remaining 10 functions are concerned with payloads, upper stages, flight feasibility analysis and utilization planning. The flight operations functions are performed in four consecutive time phases (Figure 2). The long range planning phase defines the users' cargo requirements and the required support. This phase begins two to four years prior to launch and ends at launch minus 18 months with the Cargo Integration Review. The detailed planning phase follows and is directed towards preparing a flight ready crew and ground support team and flight specific data, data loads and documentation. It terminates at launch minus two days. The flight operations phase picks up at launch countdown and continues throughout the mission until the crew exits the Shuttle after landing rollout. This real-time phase lasts up to 30 days. The post flight analysis phase is the final phase. It begins after the real-time flight operations are terminated and continues until all anomalies are resolved and data have been provided to the users and operators of the Shuttle.

Figure 1 further indicates that the SOPC flight operations functions are provided by three major elements: Flight Planning Element (FPE), Flight Readiness Element (FRE) and Flight Control Element (FCE). Figure 3 depicts the major data systems which comprise

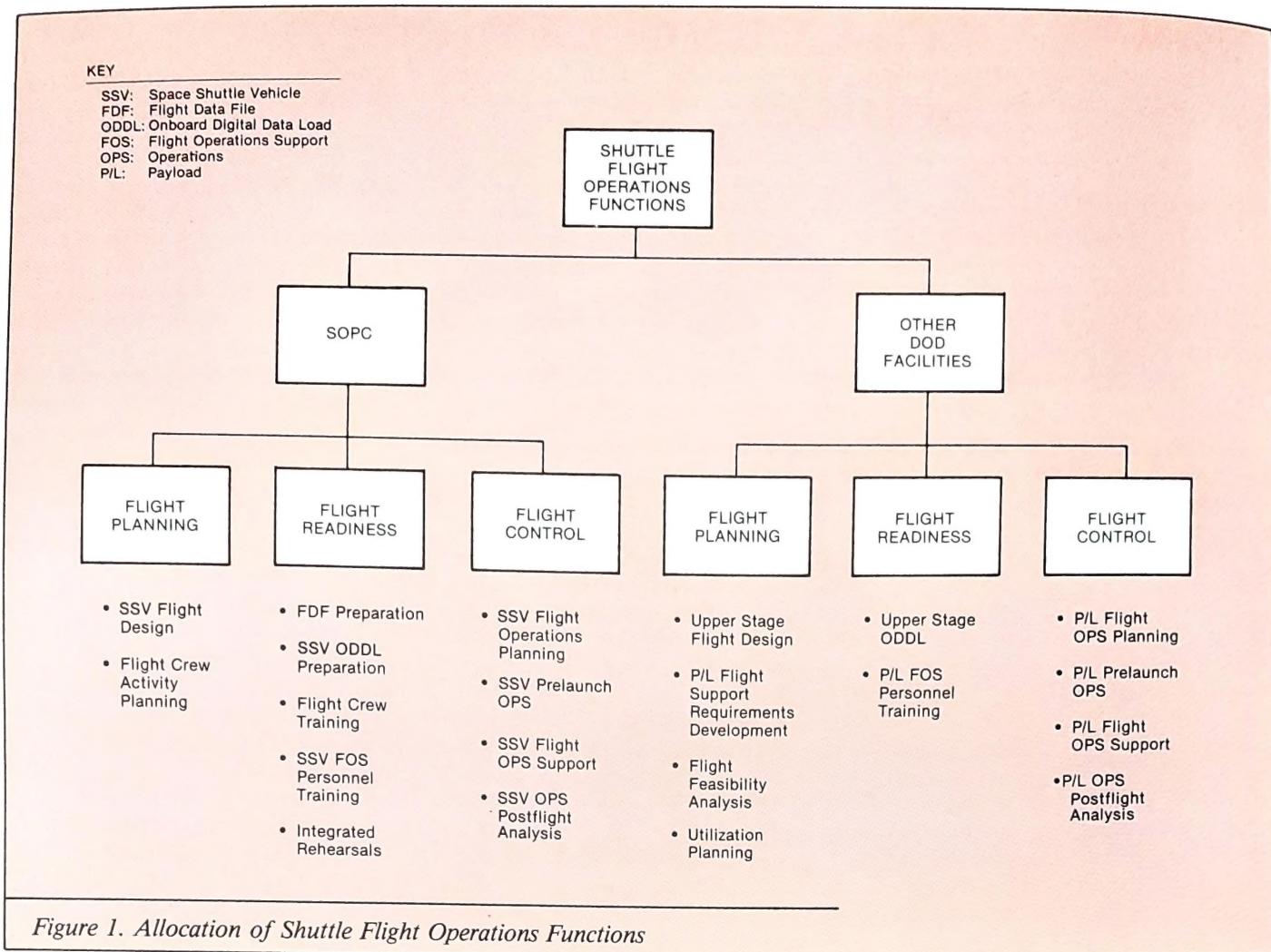


Figure 1. Allocation of Shuttle Flight Operations Functions

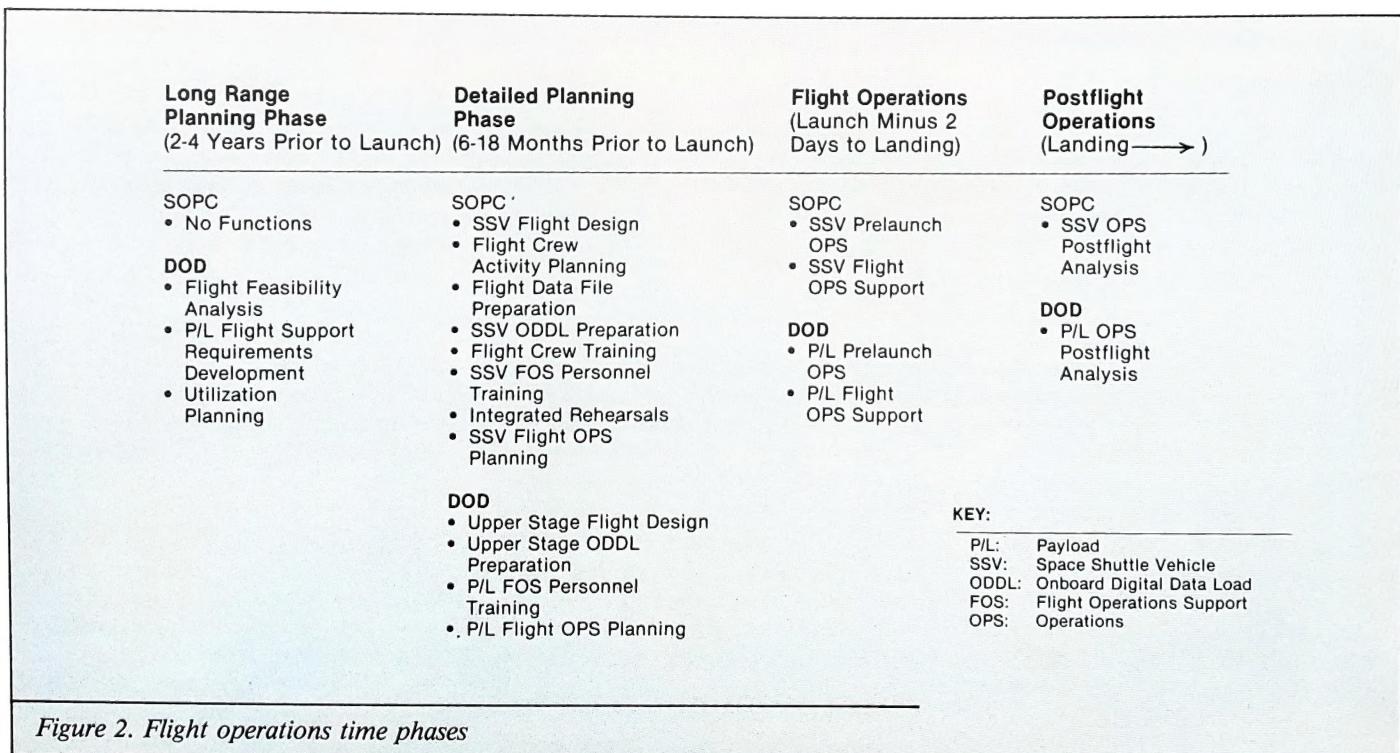


Figure 2. Flight operations time phases

these elements. These three elements provide DoD the capability to monitor and control Shuttle missions. The SOPC elements and IBM's role in their counterparts at JSC are discussed below.

Flight Planning Element

The SOPC FPE (Figure 4) provides the hardware and software products to support DoD Shuttle mission flight design activities and flight crew activity planning.

Flight Planning Element/ Flight Design System

The flight design portion of FPE is comprised of a conceptual planning system (System X) and a detailed planning system (System Y). System X is an interactive minicomputer based system that provides the models and event processors necessary for a flight planner to determine preliminary flight profiles based upon a set of mission objectives and constraints. The flight planner then uses these preliminary flight profiles as input to System Y which utilizes high fidelity models to generate precision flight data. These two systems are collectively known as the Flight Design System (FDS).

System X includes an application executive developed for NASA by IBM. In addition to the normal initialization, interface and control functions, it provides a user interface for an electronic transfer between System X and System Y. When DoD is operating in the Controlled Mode at JSC, this interface will be disabled for security reasons and a hand-carried tape will be used. At SOPC, where a secure physical configuration is available, the electronic interface and the executive will allow the flight planner to transfer the preliminary data from System X to System Y and initiate the System Y process. The data can then be returned from System Y to System X for input to an automated documentation system.

Flight Planning Element/Crew Activity Planning System

The Crew Activity Planning System (CAPS) supports the analysis and development of crew procedures and crew activity timelines during DoD flight operations. CAPS is a minicomputer

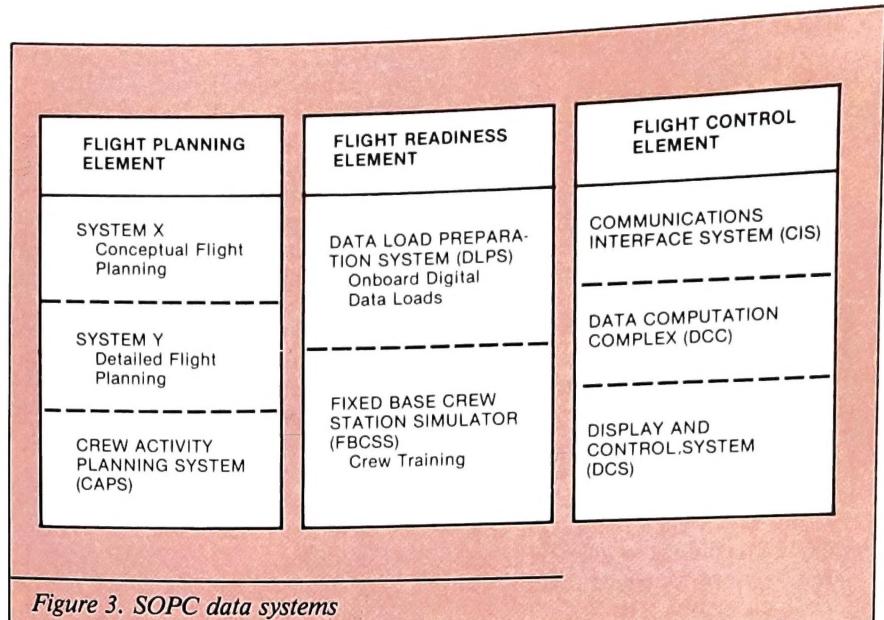


Figure 3. SOPC data systems

based system that performs timeline analysis, generates crew activity timelines, crew reference material and flight procedures checklists. It can also support near realtime mission replanning and contingency operations. The system (Level A) requirements for CAPS were written by IBM.

Flight Planning Process

The flight planning process begins when the Shuttle program office delivers a set of flight requirements and constraints to the flight design personnel.

The cargo and the objectives for the flight have already been established. From this starting point, the flight planners develop a Conceptual Flight Plan (CFP). It is a preliminary attempt to produce a flight design that determines the feasibility of the flight and technically satisfies the integrated constraints. The CFP is the basic instrument for iteration and is developed using the System X portion of the Flight Design System. This utilization of the FDS is mainly an interactive use of low fidelity simulations. The initial CFP may be generated as much as five years before the liftoff for that flight.

After the CFP has been reviewed and refined by the iteration process, work commences on the generation of the Operational Flight Plan (OFP). This may occur as much as a year before the flight and may also go through some

degree of iteration. Approximately five months before the flight, the flight design is "frozen" and the final Operational Flight Plan is published. This plan is used for flight simulations and for the System Y portion of the Flight Design System which is mainly a batch interface using sets of high fidelity simulations. Products generated at this time (e.g., trajectory tapes) are input to the Flight Readiness Element for use in onboard software and the simulator, to Flight Control for ground software testing and to the crew planning personnel for the development of the Crew Activity Plan.

Flight Readiness Element (FRE)

This element consists of two major components: the Data Load Preparation System (DLPS) and the Fixed Base Crew Station Simulator (FBCSS). The FRE provides DoD with the capability to support flight data file preparation, onboard digital data load preparation, flight crew training, flight operations support personnel training and integrated rehearsals.

Flight Readiness Element/ Data Load Preparation System

The DLPS is the SOPC version of the Software Production Facility (SPF) at Johnson Space Center which is an

upgrade to the Software Development Laboratory (SDL). It is used for development and reconfiguration of flight software to support specific vehicles, payloads and flight profiles. The SDL executes on IBM System/360 Model 75s. IBM programs the SDL and will provide the software for the SPF. The SPF procurement for the replacement of the 360/75s was recently awarded to IBM. The new machine will be an IBM 3033. The data load preparation system components will be initially installed at JSC as part of the SPF and moved to SOPC at a later date.

Figure 5 depicts a multi-flight computer configuration similar to that anticipated for the DLPS. The general purpose computers are laboratory versions of the computers onboard the Shuttle and are built by IBM. The Flight Equipment Interface Device (FEID) is a special piece of equipment also built by IBM. It provides the proper interface between the general purpose computers and a host computer which can simulate the Shuttle environment and avionic systems. Two other components of the DLPS are the mass memory unit and the multifunction cathode-ray tube display system (MCDS), provided by IBM. The mass memory unit is a magnetic tape device which contains the data loads for the Shuttle onboard digital data systems. The DLPS produces the tape which is used to load the mass memory unit. Included in the data loads are software elements for the primary avionics system, backup flight system, display electronics unit, system loader and self-test, display text and graphics, Space Shuttle main engine controller, test control sequences, payload data interleaver and telemetry format loads. The primary avionics system software developed by IBM accounts for about two-thirds of the onboard software elements. The MCDS is the interactive display system utilized by the astronauts to communicate with the onboard computers and control the Shuttle during simulations and actual missions. The DLPS MCDS is a replica of the one on the Shuttle.

Flight Readiness Element/Fixed Base Crew Station Simulator

The Fixed Base Crew Station Simulator will provide DoD with the capability to plan, conduct and evaluate flight spe-

cific training for DoD flight crews and payload specialists. Initially, flight crew training will be conducted at JSC while payload specialists will train at SOPC in an on-orbit mission simulator. Eventually, the simulator will allow DoD to conduct flight specific training of the flight crews at SOPC while generic flight training continues to be provided at JSC.

Figure 6 depicts the current JSC FBCSS of which the SOPC simulator will be an equivalent. The configuration includes a Simulation Interface Device (SID) and five flight computers built by IBM. The SID interfaces the flight computers with the simulation system and performs a portion of the avionics system modeling.

The simulator includes a mock-up of the Shuttle orbiter flight deck which provides the flight crews with a realistic training environment for all mission phases from prelaunch through rollout. Stations are provided for the commander, pilot, mission specialist and payload specialist.

All simulations are in real-time with the capability for background jobs (assemblies, compilations, delogging, prints, etc.) during simulation. Color visual scenes are created for the six forward windows, the two aft windows and the payload bay closed circuit television Cathode Ray Tubes. Aural simulations include the Shuttle mechanisms and inflight sounds as well as communication loops. The simulator contains a Network Simulation System for modeling telemetry, command and the communications and tracking network. The Network Simulation System also provides the interface to the FCE for integrated flight controller training.

There are instructor and operator consoles that have been designed to provide the capability to monitor simulations in progress and to control simulation activities. An interactive display system provides digital and graphic displays and allows faults and perturbations to be entered. Monitoring and controls are designed such that one individual can run a simulation or the full complement of instructors, operators, crew, and ground controllers can be used.

Flight Control Element

The FCE provides the hardware and software necessary to perform flight

operations planning, Shuttle prelaunch operations support, Shuttle flight operation support and Shuttle operations post-flight analysis. The FCE consists of three major systems; the Communications Interface System (CIS), the Data Computation Complex (DCC) and the Display and Control System (DCS). Figure 7 depicts these components at a high functional level. The FCE is referred to as the Shuttle Mission Control Center (SMCC).

Flight Control Element/ Communications Interface System

This system provides the interface between SOPC and the DoD network. It also performs preprocessing, recording and distribution of telemetry, tracking, command, video, voice and miscellaneous data within the SMCC and external sources. It is highly reconfigurable (as is the SMCC in general) and provides flexible data paths for the same data type or unique data paths for specific data.

For example, the high speed launch and landing C-band tracking data from Kennedy Space Center (KSC) is routed through a very short path in the CIS via a Launch/Landing Interface Unit and handled by special software in the DCC. S-band and low speed tracking data of all types is processed through a slightly longer routing function but is passed to the DCC without preprocessing whereas the telemetry data goes through data quality, routing and decommutation functions before being sent to the DCC.

The communications segment for SOPC has many functions in common with its counterpart in SOC. It is very likely that these functions will be provided to SOPC and SOC via a common CSOC communications segment. The exact functions and equipment to be shared will be determined at a later date.

Flight Control Element/Data Computation Complex

The DCC provides the major computational capability for the Flight Control Element (FCE). It also provides switching and peripheral capability and is composed of three major components: the Shuttle Data Processors (SDPs), the Multi-bus Interface (MBI) and the Configuration and Switching Equipment

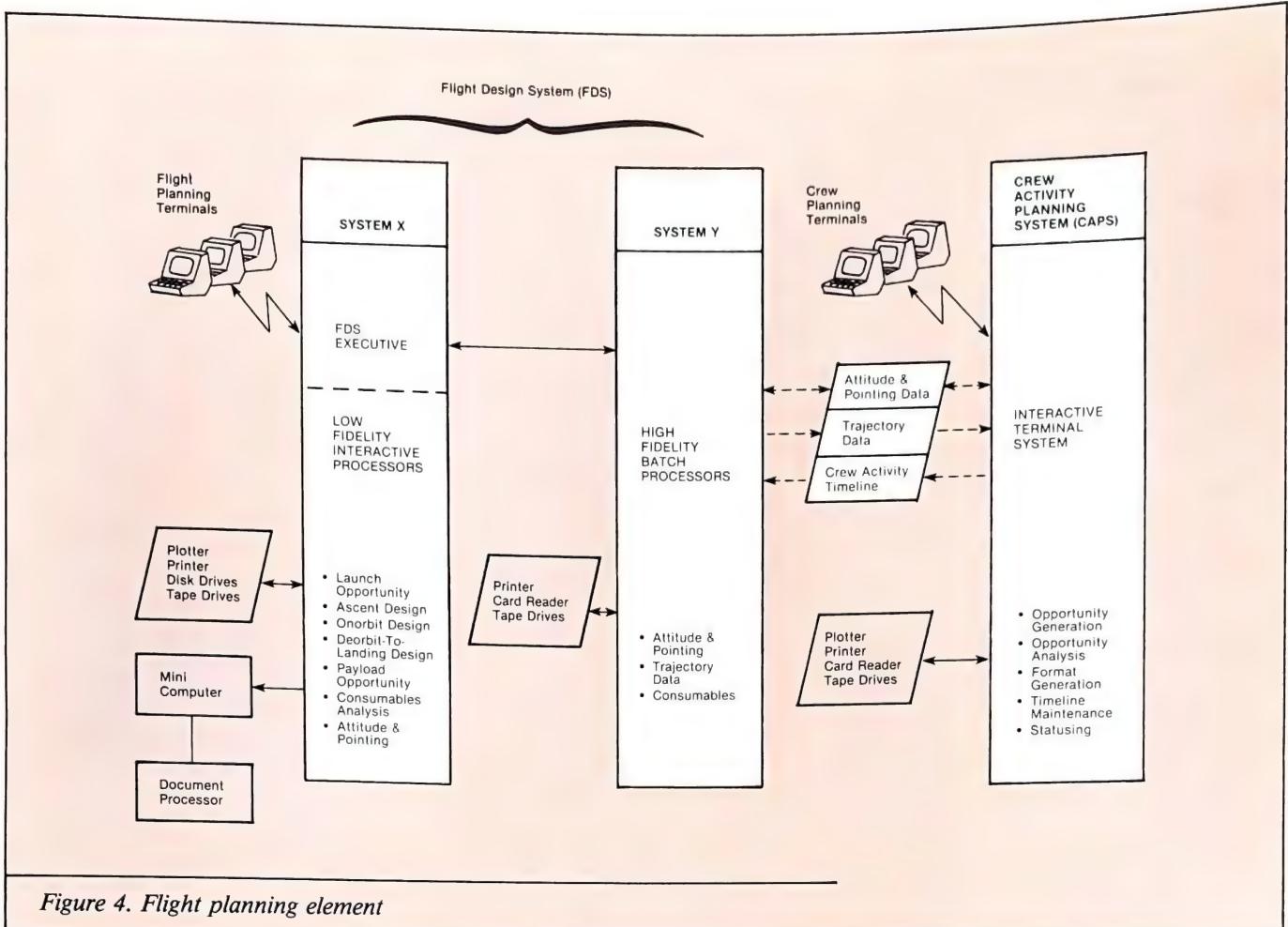


Figure 4. Flight planning element

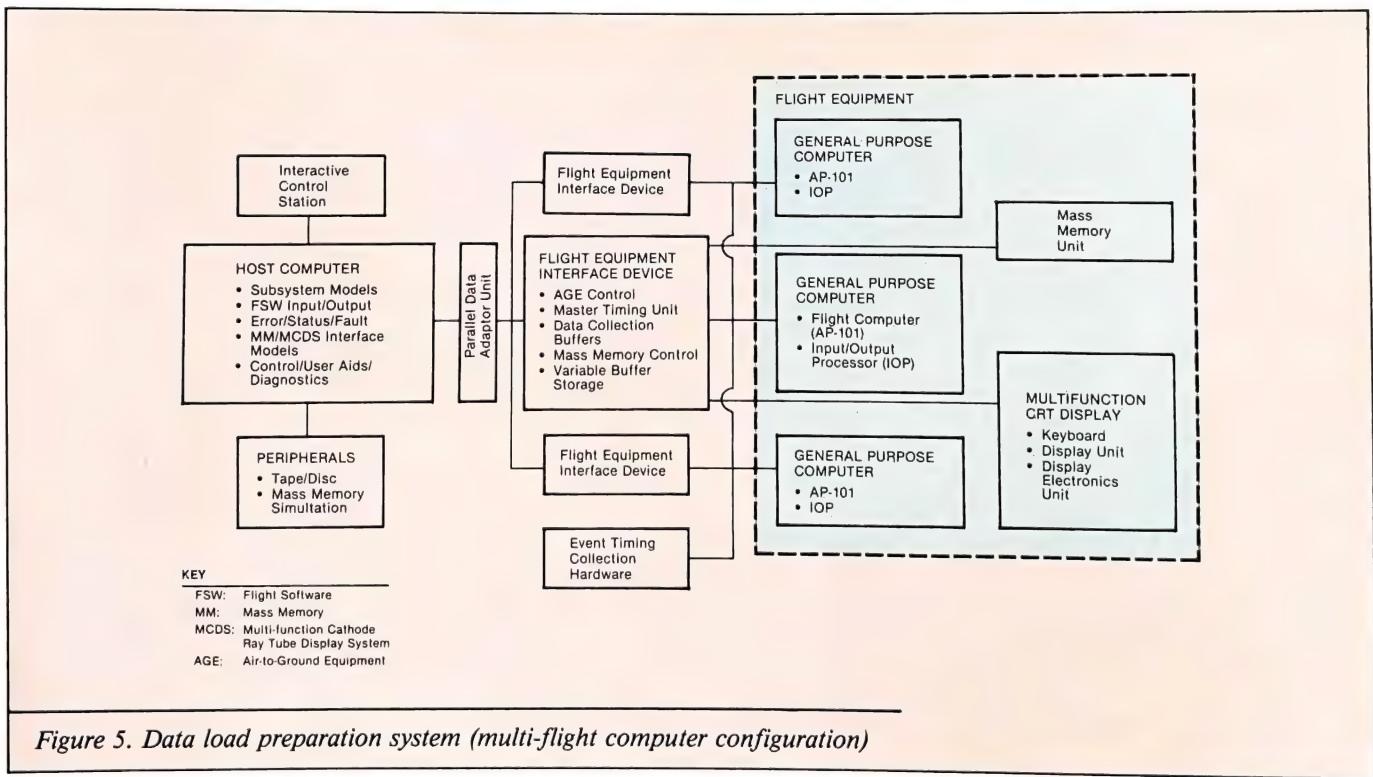


Figure 5. Data load preparation system (multi-flight computer configuration)

(CSE). Figure 8 gives an overview of the major data flows and paths between the DCC and other SOPC and DoD components.

The DCC has a switching capability that provides multiple high speed paths between the components of the CIS and the SDPs. A particular path through the CIS and DCC when coupled with a set of DCS operator consoles is commonly referred to as a flight control string. The SOPC will eventually have a dual string capability which could provide simultaneous support for two live missions, or one live and one simulation. In a non-mission environment, development work will also be performed on a string or some portion of one.

The SDPs are a set of large host computers. For Controlled Mode at JSC, the

SDPs are four IBM System 370/168s. For SOPC they will be three or four (to be determined) current technology, upward-compatible replacements. The DCC is where the major real-time command and control processing is performed in support of DoD Shuttle missions. The applications which reside in the SDPs include telemetry, trajectory, command, network communications and an application executive. These applications span the mission events from pre-launch to vehicle rollout. Figure 9 shows the mission phases in a typical mission profile. In addition to the real-time programs, there are many offline or near-real-time programs used to support the real-time and development environments. Included are such functions as hardware checkout, software

checkout, flight-to-flight reconfiguration, statistics collecting, performance analysis and system build facilities.

The DCC software (developed by IBM) is large and complex. The current size of the Flight Control Element software at JSC is in excess of two million source lines of code (SLOC). It is anticipated that by the time this software is transferred to SOPC it will have grown, due to new requirements, to over two and one-half million source lines. This software is the largest component of the SOPC total (including FPE, FRE and FCE) of a projected 5.3 million lines. Figure 10 shows the projected sizes of the major SOPC software components.

The CSE provides the capability to configure the SDP with communications

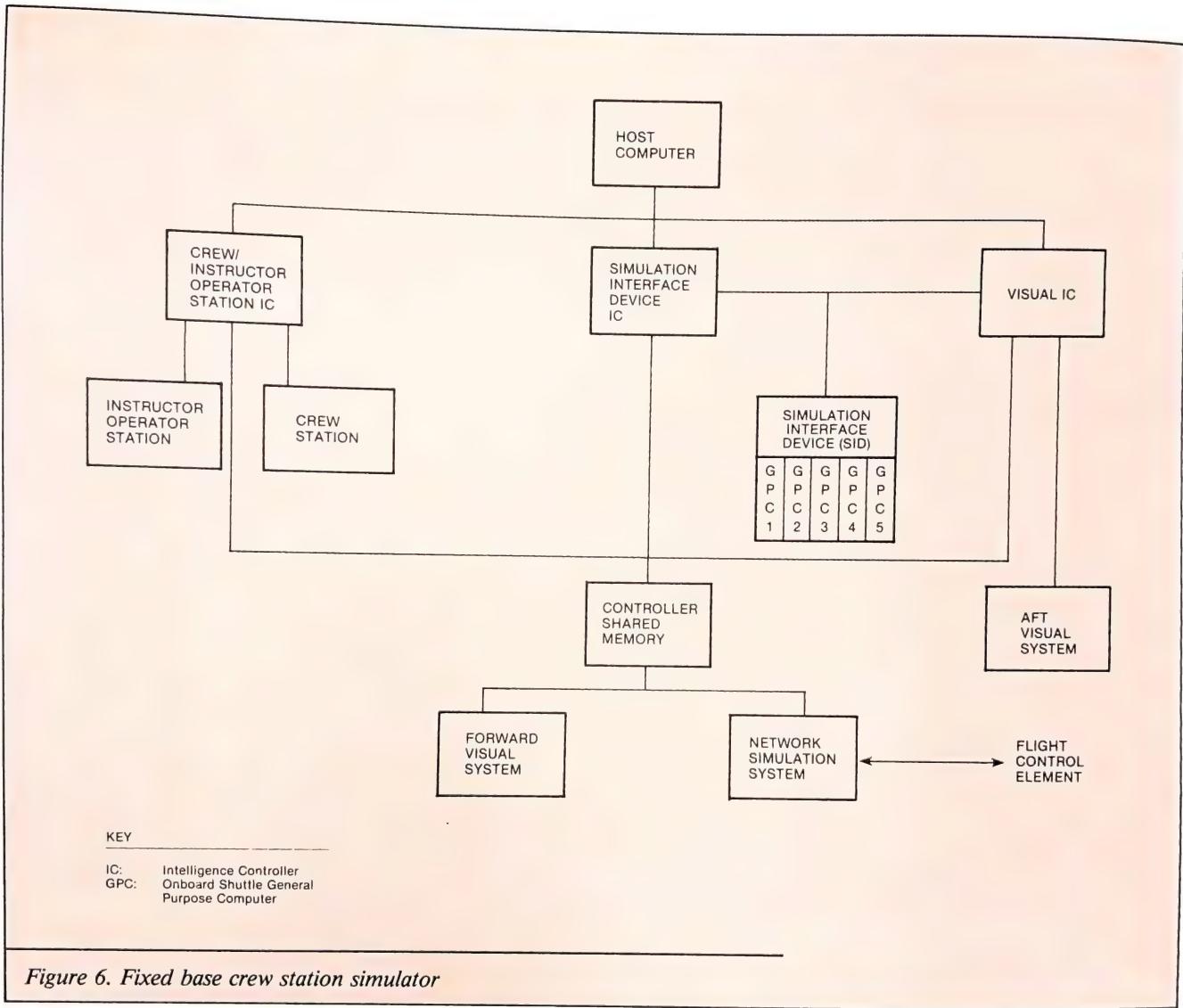


Figure 6. Fixed base crew station simulator

equipment, shared peripherals and the DCS. It also supports selectover (switching to another computer) in the event of SDP failure or scheduled maintenance.

Flight Control Element/Display and Control System

The Display and Control System provides the capability for mission and support personnel to request and moni-

tor computer processed data in several media. The mission consoles at JSC are somewhat familiar to the viewing public as they are the ones usually televised during live mission coverage. These consoles have functional keyboards, television equipment, analog and event indicators and means for requesting data from the CIS and DCC and for initiating commands and configuration instructions to FCE equipment and the Shuttle. In addition to the display

subsystem and the control subsystem whose functions have just been discussed, the DCS also provides a timing subsystem which is the master timing service for all SOPC systems.

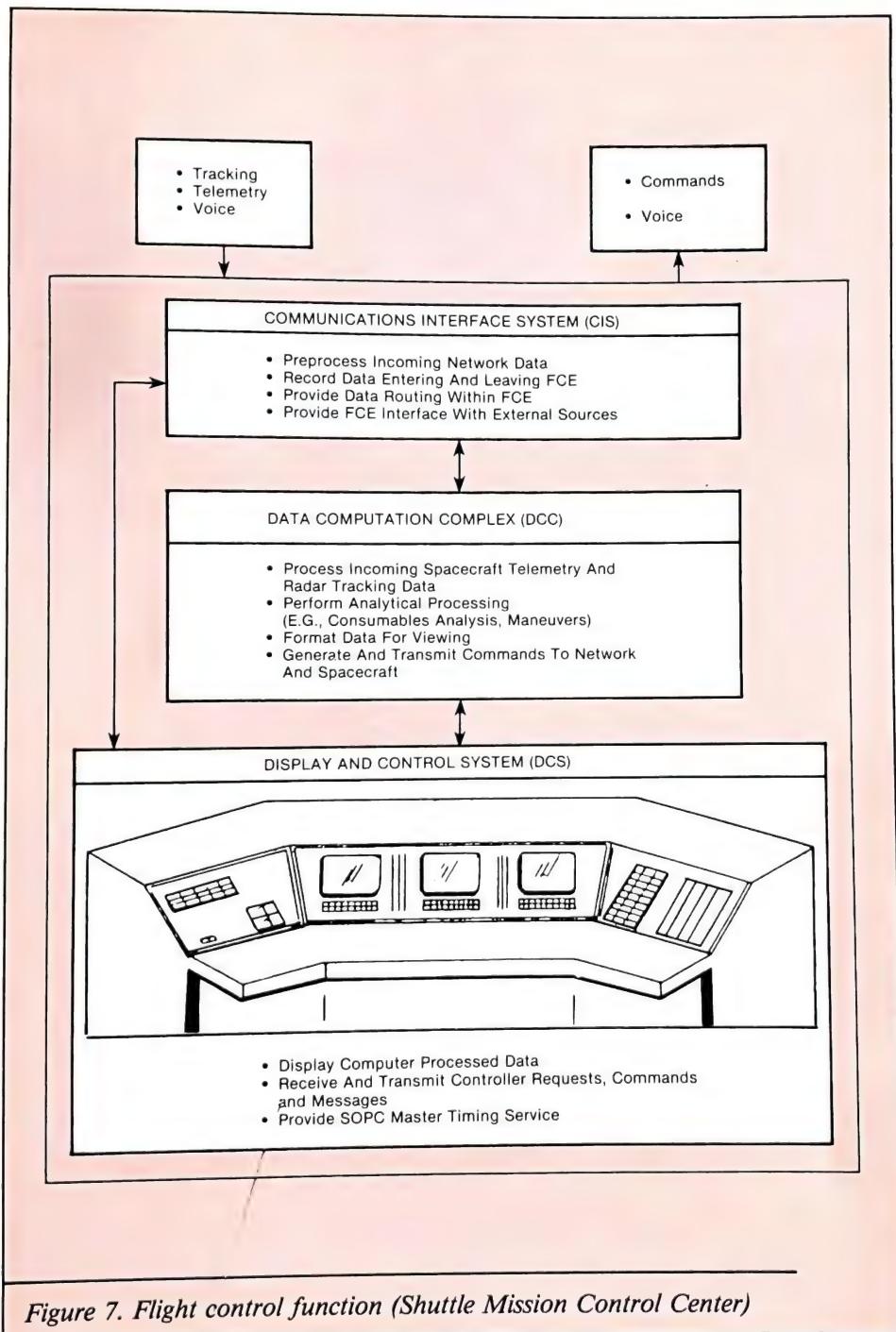
Mission Development and Support

At this point the major SOPC elements and their functions have been discussed. A typical timeline and data flow through these elements and how they are used to prepare for and support DoD flights will now be described.

The scenario for a DoD Shuttle mission involves the launch site (Kennedy Space Center or Vandenberg), tracking network, the Shuttle vehicle, and SOPC (Figure 11). The mission sequence begins some three to four years prior to launch with the commencement of payload activities but the publication of the Payload Integration Plan (PIP) annexes at launch minus two years (L-2 yrs.) is a better indication of the start of the mission process.

There are two complexities of DoD flights to be considered. Low complexity is a repeat flight while high complexity is a first of its kind. The schedule of events is similar in content but the timelines are noticeably different. A timeline for software reconfiguration for the low complexity case is shown in Figure 12. The Mission Definition Change Request would occur at launch-234 days for the high complexity case as compared to launch-128 days for the simpler one. The current assumption for the operational SOPC era is that 80 percent of the DoD flights will be of the repeat variety.

Considering the low complexity case and referring to Figures 11 and 12 it is seen that the Mission Definition Change Request appears at L-128 days. This document specifies such items as payload, orbiter, trajectory and crew. This information and data generated from it begin to feed the components of the system. The Master Measurement Data Base (MMDB) is the major source for all SSV related measurement and stimuli information such as uplink and downlink formats, calibration constants, channelization data, command lists and data definitions. Products containing this information are generated and sent to other systems for utilization in mission related functions.



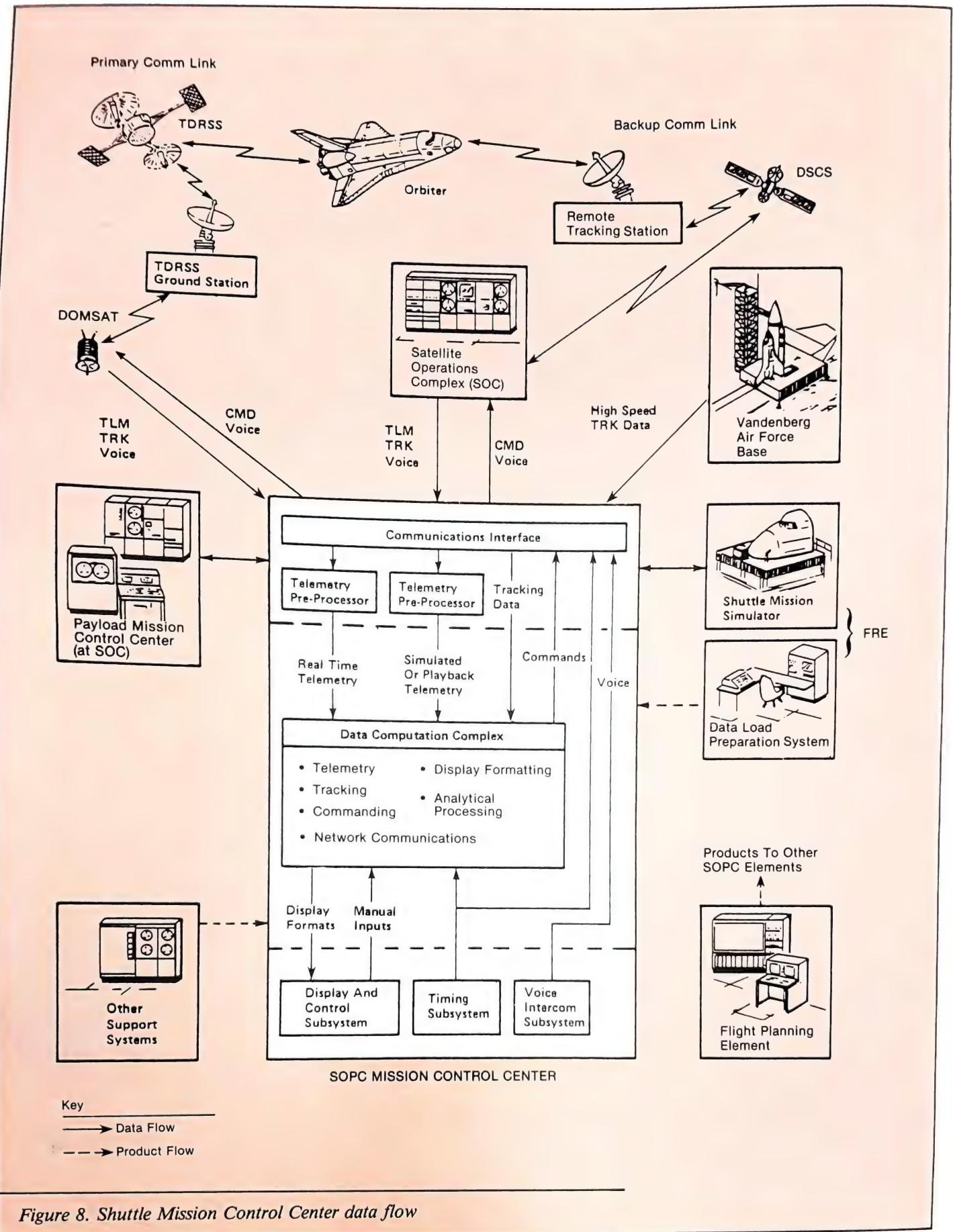


Figure 8. Shuttle Mission Control Center data flow

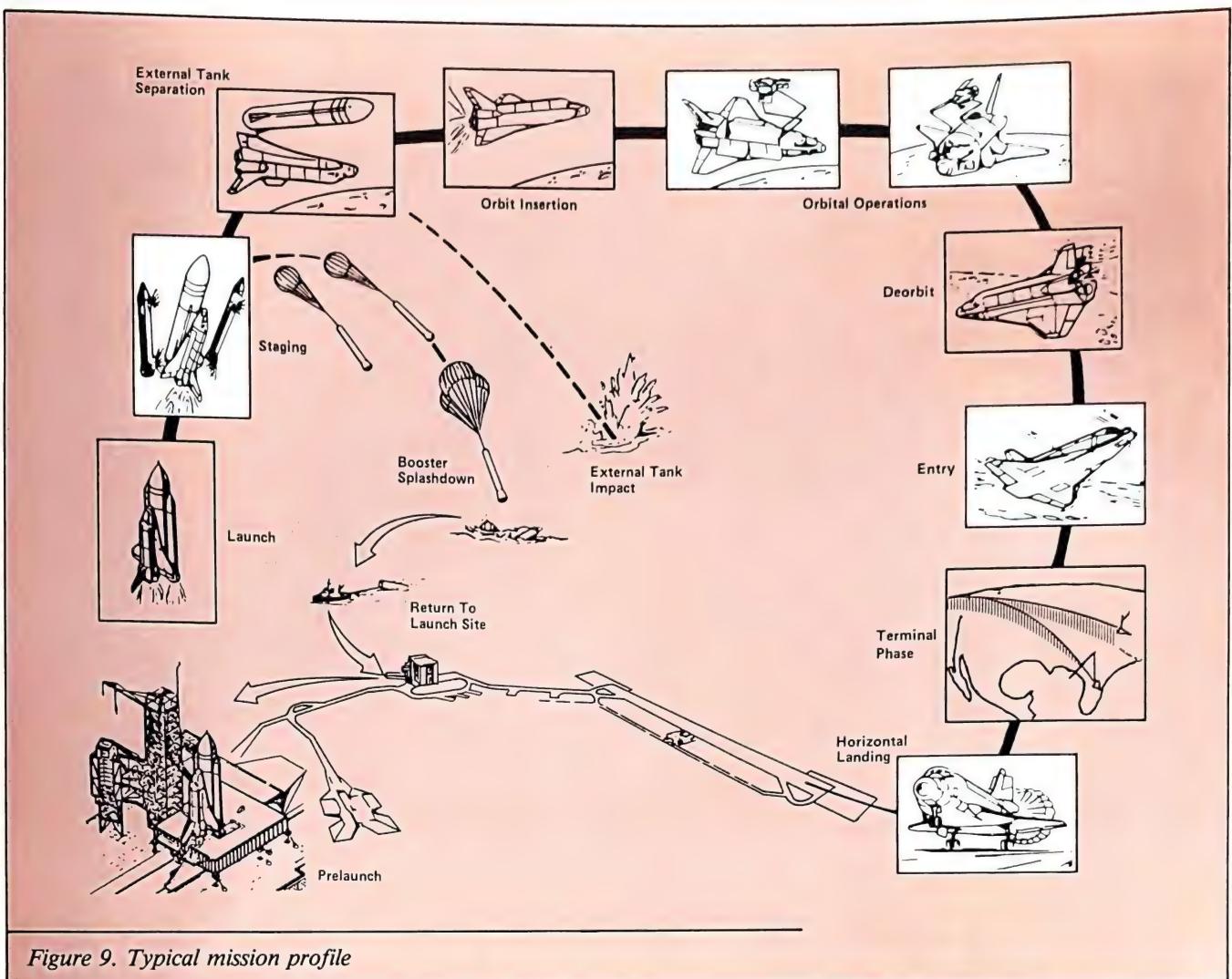


Figure 9. Typical mission profile

Thousands of Source Lines of Code*	
FLIGHT CONTROL	2512
CIS (356)	
DCC (2156)	
DCS (0)	
FLIGHT READINESS	2275
DLPS (1201)	
FBCSS (1074)	
FLIGHT PLANNING	547
SYSTEM X (259)	
SYSTEM Y (188)	
CAPS (100)	
<hr/>	
	5334

*Includes embedded comments

Figure 10. SOPC projected software size

Configuration Requirements Processing (CRP) utilizes the MMDB data to generate reconfiguration products for other parts of the Flight Control Elements. The CRP products for a typical flight may consist of over 7000 products containing 600 megabytes of data and include air-to-ground telemetry data, calibration constants, limit values, command data, vehicle performance data, SMCC configuration data and a wide variety of trajectory constants and model data.

The DLPS produces mass memory load tapes for the onboard flight computers in the Fixed Base Crew Station Simulator and for the launch site to load the Shuttle onboard computers. The mass memory load tape has software elements for the primary and backup flight software systems, Space Shuttle main engine controller, display

units and other items like system loaders and telemetry format loads.

Meanwhile the Crew Activity Plan (CAP) and the Flight Data File (FDF) are being generated. The former specifies detailed crew activity timelines and the latter specifies reference material for payload or Shuttle activities. The FDF includes such items as system checklists, reference data and hardware such as clips, tethers and bags. At this point the SSV, the launch site and the Flight Readiness, Planning and Control Elements are synchronized on the same data loads and can run integrated simulations, rehearsals and various types of pad tests.

It should be clear that the above scenario is a single, simplified sketch of what is a complex process involving considerable feedback, multiple iterations and multiple versions (revision

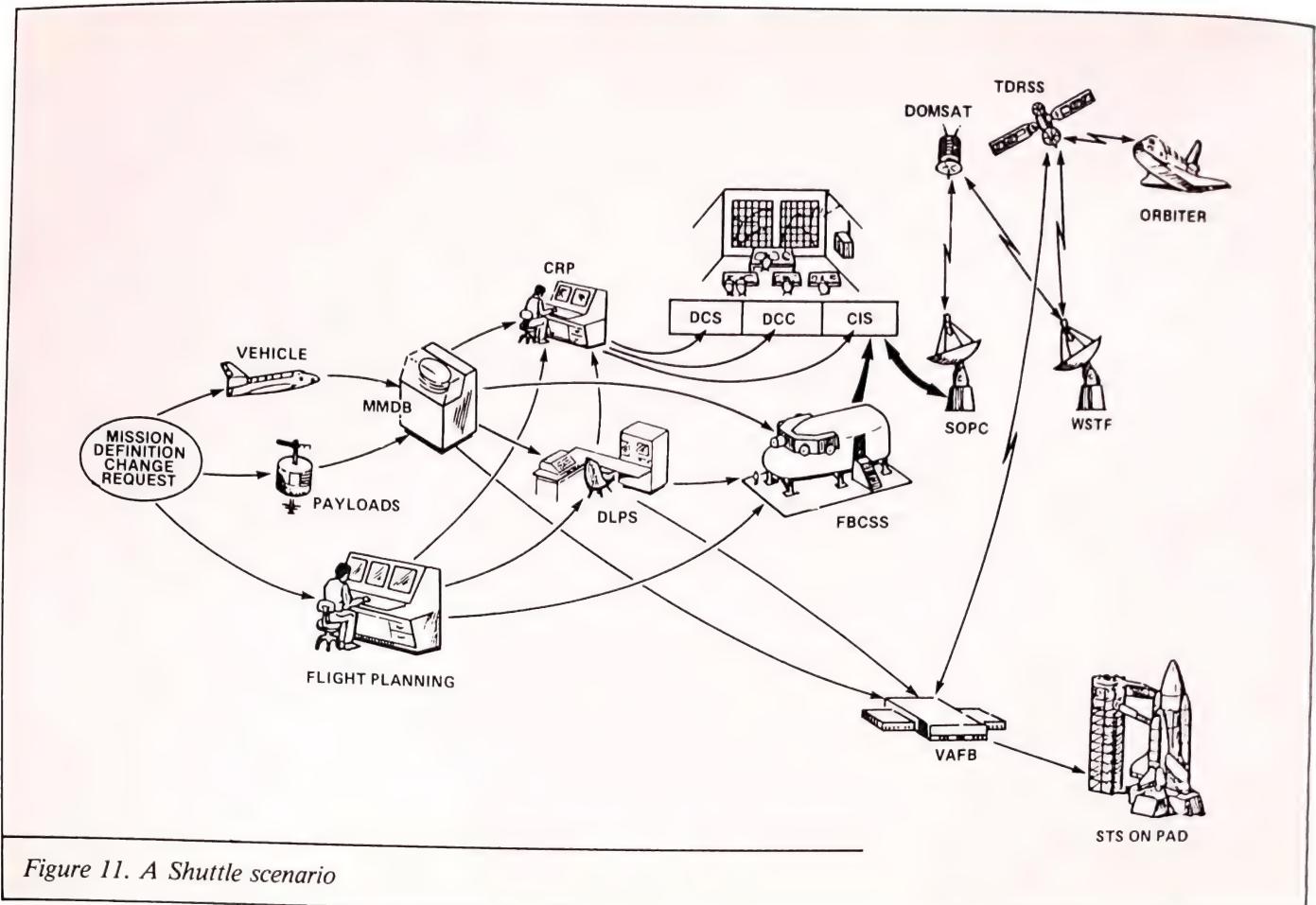


Figure 11. A Shuttle scenario

levels) of the data involved. Consider that for the DoD traffic model, there will be multiple missions at some stage of development at the same time and it becomes evident that configuration management and flight-to-flight reconfiguration tools are very important parts of the SOPC function. In essence flight-to-flight reconfiguration is the process of including flight specific data in a selected set of off-the-shelf software elements to create a software package for each data system for support and operation of a given flight.

Mission Types

The utilization of the Shuttle provides DoD with the capability for a greater variety of mission types than possible with unmanned, non-returnable vehicles. In addition to the deployment mission, DoD can now perform retrieval, on-orbit servicing, on-orbit checkout, space construction and sortie missions.

A sortie mission is one in which the

payload remains attached to the Shuttle Orbiter and returns with it after a stay of up to thirty days in space. The sortie mission represents more involvement with the payload than normally envisioned for SOPC. This is because SOPC is a Shuttle oriented and not a satellite (payload) oriented facility. Once the payload is deployed, control of it is assumed by SOC where the payload data is processed by a Payload Mission Control Center (PMCC) within SOC. It was noted earlier that current plans are for SOC and SOPC to be co-located at CSOC.

In addition to the mission types just discussed, a current DoD capability called flexible launch is required for Shuttle missions. Flexible launch refers to the capability to launch a spacecraft within a specified number of calendar days after notification. The concept involves performing the flight preparation and readiness activities and then putting the system on hold. Periodic updates may be made until launch call is received at which time activities are

resumed, leading to a launch within the specified time frame, less than the 128 days required for low complexity missions. The objective of flexible launch is to provide DoD the capability to quickly replace a disabled or malfunctioning satellite.

Transition/Interoperability

It has been previously mentioned that prior to an operational SOPC, DoD Shuttle operations will be conducted at JSC in the Controlled Mode environment. Close coordination will be required to transition from JSC to SOPC. The key elements of transitioning are direct DoD participation in Controlled Mode, utilization of NASA support and configuration control procedures and a phased, incremental, parallel approach to SOPC prime mission operations capability. The Air Force Manned Space Flight Support Group (MSFSG) stationed at JSC will support development and operations for DoD flights in Controlled Mode. MSFSG will also train flight oper-

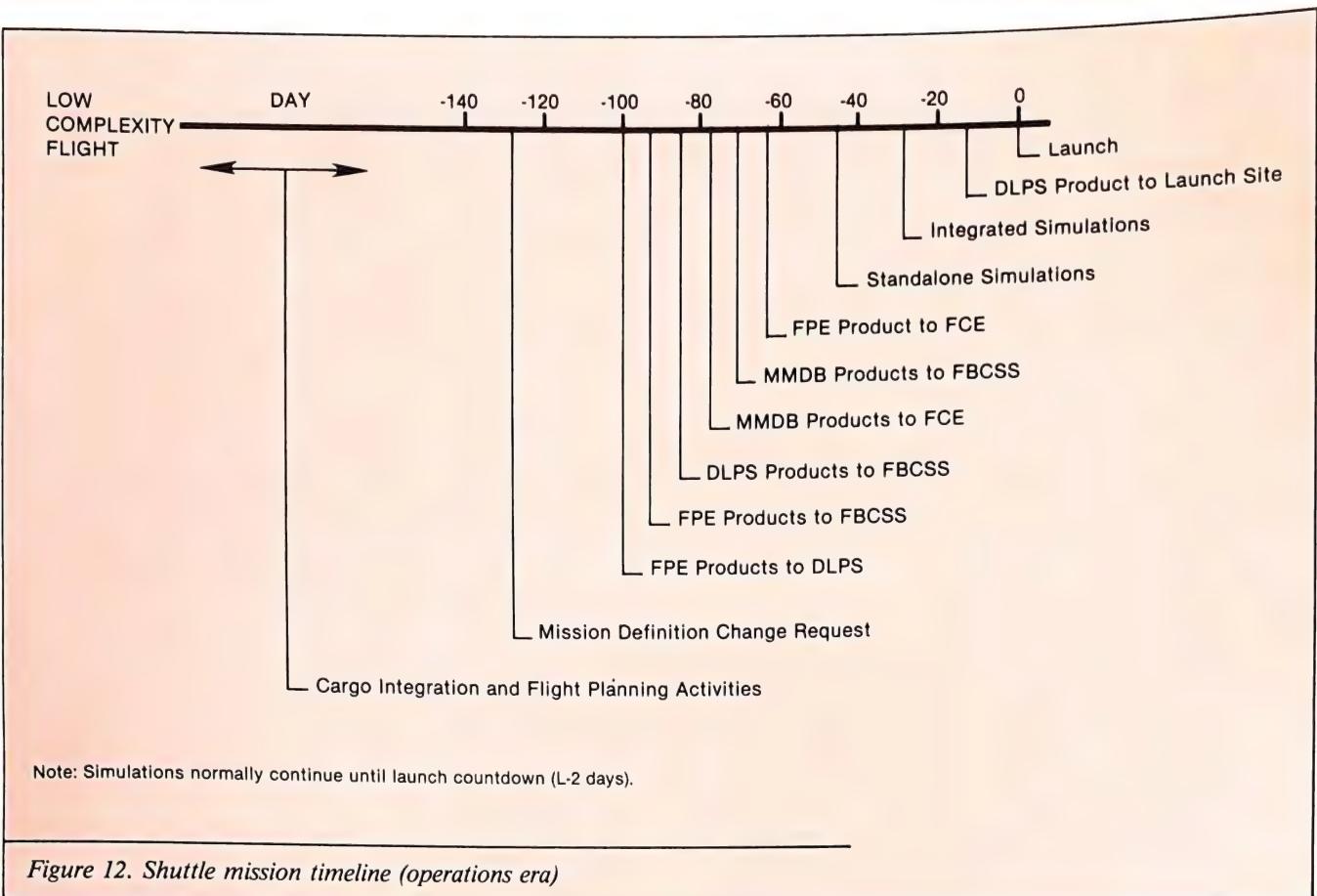


Figure 12. Shuttle mission timeline (operations era)

ations support personnel who will transition to SOPC to form the initial cadre.

SOPC operational readiness will begin by running off-line with NASA provided flight tapes. Later, SOPC will function as live backup to a prime JSC for a DoD flight. Then, JSC will serve as a live backup to a prime SOPC for a DoD flight. SOPC will then assume a prime operational role with JSC in a cold standby or "call-up" mode. The plan calls for SOPC to use a Global Positioning Satellite (see article on page 26) repeat flight to assume prime operational support.

The SOPC/JSC interoperability requirement could place stringent configuration control procedures on both SOPC and JSC even after the transition phase. In essence, interoperability is the requirement for one center to perform specified functions of another center. For example, if SOPC were unable to continue mission support due to natural or man-made causes, it is required that JSC be able to provide the necessary support to continue and con-

clude the mission.

This requires some degree of similarity in hardware, software, procedures and configuration products. The similarity could range from functional capability to identical replication and the exact degree has yet to be determined. Suffice it to say that initiating DoD Shuttle capability at JSC, developing SOPC and then transitioning to an operational SOPC while maintaining interoperability with JSC presents a noteworthy challenge.

Summary

The major activities for SOPC in the Shuttle operational era will be to reconfigure the software data systems, to train flight crews and flight operations support personnel and to control and monitor DoD Shuttle missions. The software reconfiguration is driven by changes in the vehicle, payloads, or mission profile. The concept for reconfiguring the software is that it will be mature and development will be at a

very low level. Therefore, reconfiguration is viewed as a data manipulation and verification process. To support the fast turnaround required by the DoD traffic model and to minimize the SOPC staffing level, there will be standardization of mission phases, reuse of data sets and more software tools to provide a high degree of automation. Flight crews will be provided by NASA and will receive flight specific training at SOPC. Flight Operations Support personnel will be trained using SOPC training systems.

DoD and NASA are addressing flexible launch, interoperability, dual flight support, standard mission phases, JSC-to-SOPC transition and staffing level as well as the operational SOPC activities of flight-to-flight reconfiguration and flight personnel training. The tools and procedures being developed are aimed at providing DoD a low cost, reliable means for launching satellites and conducting space operations.

The Launch Processing System for STS and DoD Space Shuttle

by Don G. Satterfield

Introduction

The all-digital Launch Processing System (LPS) passed a major test in the checkout and launch of the first reusable Space Transportation System in April 1981. Its outstanding performance demonstrated that the LPS can support the fully operational Space Shuttle program, including the planned DoD launches from Vandenberg Air Force Base, California.

The LPS was developed by the IBM Federal Systems Division at its Cape Canaveral facility in conjunction with NASA at the Kennedy Space Center. The LPS concept reduces cost, minimizes launch turnaround time and increases the efficiency and effectiveness of the Shuttle launch team, thus enabling the size of the team to be significantly reduced from the more than 200-person team needed to launch an Apollo/Saturn vehicle. The need to automate checkout was evident very early in the Shuttle program if sufficient reductions in time from landing to re-launch were to be realized.

This article reviews the history that indicated the need for a better system to launch reusable space vehicles (Figures 1 and 2). Also discussed are: the LPS architecture using commercially available minicomputers, the challenges the design team faced in achieving a high level of system availability while controlling potentially hazardous functions (to both crew and vehicle) in a closed loop configuration (Figure 3), and the fault detection scheme and redundancy built into the system. The latter is to assure no impact to testing due to a hardware failure. Examples of these features are presented to indicate the protection provided for safe and reliable operations. Fault tolerance techniques were implemented in the LPS in those instances where redundancy was not a practical consideration. The

article concludes with a summary of STS-1 performance data and a discussion of the future for LPS.

Problem

The challenge for the LPS designers was to develop a distributed minicomputer system that meets the stringent availability requirements for supporting checkout and launch of the reusable Space Shuttle. The critical functions to be controlled in the real-time system dictated rapid fault detection, resolution and reconfiguration.

History

The manned space launches of the late 1950s and early 1960s were accomplished with the use of very little automation. Issuing commands to the vehicle and responding to out-of-tolerance measurements were accomplished almost entirely by people aided by semi-automated launch sequencers. Subsequently, the commitment to land a man on the moon and return him safely to earth in the decade of the Sixties dictated the need for state-of-the-art vehicle checkout and launch team capabilities. This task was performed



Figure 1. Firing room at Kennedy Space Center as it appeared for launch of Apollo 11 and the first lunar mission.

by two ground computers for the Saturn IB and Saturn V launch vehicles.

These ground computers were transistorized, large-scale, serial, digital computers. The one located in the Launch Control Center (LCC) communicated, via a data link, with the other computer, located 3.5 miles away within the Apollo/Saturn Mobile Launcher (ML). Being serial computers, they were relatively slow (28 usec word time); however, they had the capability of issuing 2000 unique commands to the Launch Vehicle, while monitoring and performing limit checking of several thousand measurements. IBM's Federal Systems Division designed and developed the ground computer software and, in addition, the Division operated and maintained the ground computer system.

The two computers for checkout and launch of the vehicle were required to be operational and on-line (there was very little redundant or backup hardware); there were numerous single-point failures which could abort or cause a hold in vehicle checkout and launch. Another disadvantage of this system was that nearly 50 percent of the hardware was located within a few hundred feet of the launch vehicle. This occasionally meant that corrective maintenance had to be performed by people in a very hazardous area.

On most programs, where high availability and stringent throughput requirements exist, the system objectives are achieved using custom hardware built to MIL-SPEC standards. However, while highly successful for Apollo/Saturn goals, this approach could not meet the Space Shuttle objectives to reduce both development and operational costs. One-of-a-kind hardware with special case maintenance and sustaining engineering is expensive. Therefore, highly reliable parts were selected for use and lot shipments of parts were closely tracked through every phase of handling.

New Concept Dictated

A new concept for the automated checkout and launch of the Space Shuttle was clearly dictated. In short, to meet the rapid turnaround time requirement of a reusable vehicle as well as to significantly reduce the number of people involved, the entire launch pro-

cessing activity had to be automated with digital computers. But it had to be done in such a way as to preserve, from a functional point of view, the test engineer's direct control over checkout and launch procedures. Therefore, a highly functional interface (Figure 4) between the user-engineer and the system was necessary, one that would not rely on a programmer to interface between a user and the system. This meant automation all the way from the test engineer up to the launch vehicle.

In 1974, IBM was selected by NASA as co-architect to provide System Engineering and Software Development for the Launch Processing System. This

selection, prior to hardware and computer procurement, allowed a total system design to be put in place for the LPS as contrasted to previous programs where the hardware was selected first and the software was then required to fit a "committed-to" system architectural design.

This option was key to the success of the program. The NASA-IBM team conducted numerous trade-off studies to determine the allocation of processing functions. The results of these studies were tested and simulated to predict effectiveness and performance for each key decision.

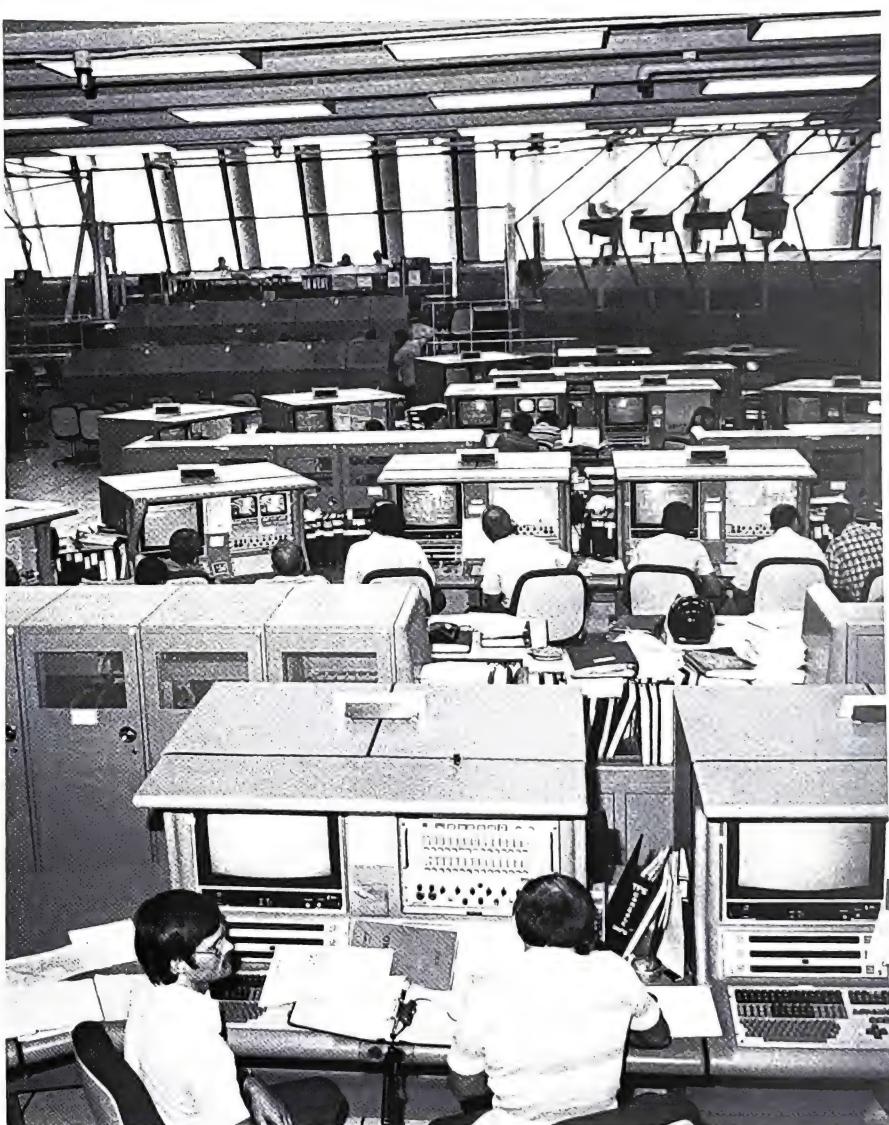


Figure 2. Firing room at Kennedy Space Center powered up for the integrated test of Space Shuttle Columbia, STS-1.

Distributed Minicomputer Network Architecture Selected

A distributed minicomputer network architecture was selected, one in which up to 64 minicomputers or microprocessors share a common 64K-word, high-speed pipeline memory to communicate with each other. These computers perform basically five functions:

- (1) allow the operator to interface directly with the machine
- (2) interface with Ground Support Equipment to issue commands and monitor and limit check measurements
- (3) interface with the Orbiter on-board computers of the IBM avionic subsystem to issue system commands

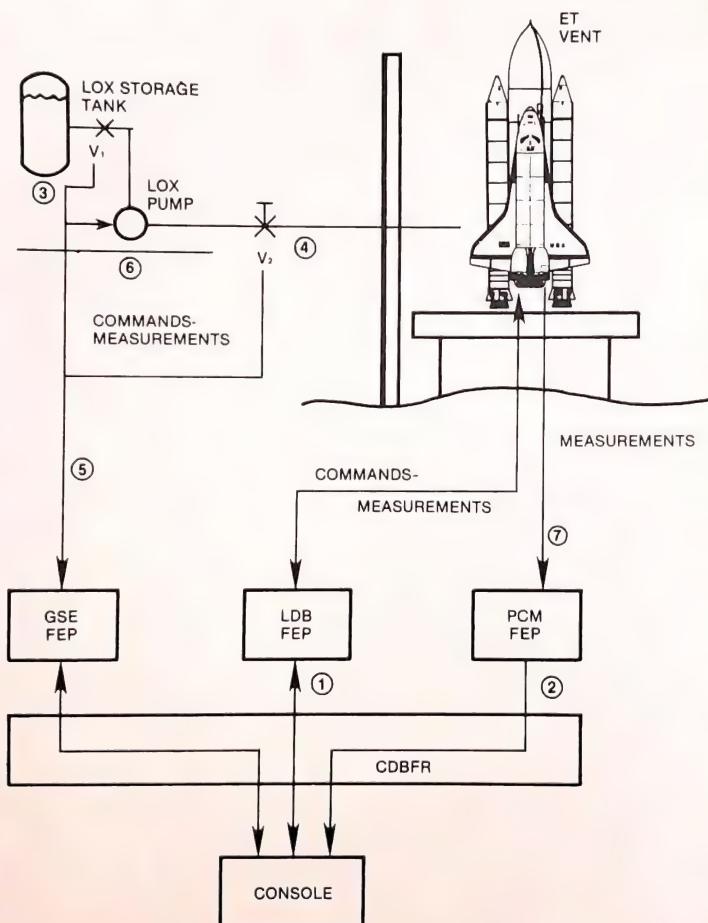
and monitor data

- (4) record most transactions in the 64K shared memory
- (5) provide the capability to retrieve, format and print these pre-recorded transactions.

Commercial minicomputers (MOD-COMP II/45) were selected by NASA for the operational system. Each computer was upgraded to contain two asynchronous microprocessors, hereafter referred to as "option planes." These option planes provide the capability to implement "smart" I/O channels and contain 1K words of 44-bit micro-programmable Read Only Memory (ROM) and, in some cases, 1K-words and 16 bit scratch pad Random Access Memory (RAM). The CPUs are 16-bit parallel computers containing up to 64K

words of executable memory and up to 256K of non-executable memory. Communication between a CPU and its two option planes is provided via the CPU instruction set, CPU memory, and Option Plane-to-CPU interrupts.

A key capability of the system is an inherent capacity for parallel testing of the launch vehicle. This means that from their consoles, test engineers engaged in the performance of separate procedures can invoke the necessary support of other subsystems with minimum interference with other test procedures running against those subsystems. The necessary access of these supporting subsystems must be available to the test engineers without tying up any other test engineers. Also, the processing and monitoring of more



Acronyms

LOX - Liquid Oxygen
FEP - Front End Processors
GSE - Ground Support Equipment
LDB - Launch Data Bus
PCM - Pulse Coded Modulated Telemetry
CDBFR - Common Data Buffer
ET - External Tank
V _{1,2} - Electromechanical Valves

Simplified Application Program- Start LOX Load

Steps

- 1 - Open ET vent (command)
- 2 - Verify ET vent open (meas.)
- 3 - Open V₁ (command)
- 4 - Open V₂ (command)
- 5 - Verify V₁ & V₂ open (meas.)
- 6 - If ET vent & V₁ & V₂ open then start LOX pump (command)
- 7 - Monitor tank pressure and level measurements

Close Loop Control

If ET pressure excessive
Or ET vent fails closed
Or V₂ fails closed
Or V₁ fails closed
Then stop pump

Figure 3. An example of a closed loop configuration.

than 40,000 test parameters must be supported with real-time response capability. And, the evaluation of test results must be near real time.

LPS Architectural Overview

A block diagram of the system that supported STS-1 is shown in Figure 5. There were 41 minicomputers involved in the checkout and launch of STS-1. Active and standby computer combinations are used to assure system availability for key functions the LPS must support. However, this approach was not practical for the communication center of the network, the Common Data Buffer (CDBFR). The techniques implemented to assure data integrity for the CDBFR data transfers are discussed later in the article.

The elements of the LPS fit into seven functional areas:

- Common Data Buffer
- Operator Control Stations
- Front-End Processors (FEPs)
- Data Recording, Retrieval, and Monitoring
- Hardware Interface Modules (HIM)
- Transmission Line Conditioning and Switching
- Host Computer

Common Data Buffer

The Common Data Buffer is a 64K, 16-bit word and a 16-bit Error Correcting Code (ECC), 200 nanosecond N-MOS memory device that provides the communication center for the LPS. The common high-speed, shared memory is packaged in 32 cards of 64K by 1-bit memory planes. It provides for interrupt driven communications between computers and manages access contention through a time-shared polling system of each connected processor. Any processor can "read" data from any location but "writes" to the CDBFR are restricted to predetermined private "write" areas.

Thus, buffer overloading, which could cause an inordinate amount of buffer control overhead resulting in a data flow bottleneck, is avoided by allowing each computer to send only one message at a time to each of the other computers. The first message must be processed by the receiving computer before a second message can be sent. One computer can, however,

send a message to 32 different computers at one time. Stack registers are provided to prevent overflow and message loss.

Special microcode is resident in each minicomputer for interface with the common data buffer. Time reference for the LPS network and network switching is provided by using microprocessors interfaced to the buffer.

Operator Control Stations

Fifteen operator control subsystems are provided, each subsystem having three operator stations. A minicomputer supports each subsystem. Data are displayed on a character graphic, color CRT display system. Commands are executed and application procedure control is exercised via the keyboard, program function key, or a programmable function panel. Up to six application programs can be executed concurrently in each console subsystem. A combina-

tion printer/video copier is also provided to each console subsystem. The operator CRT position can be operated as part of the real time system or as a remote terminal to the host machine. These control stations are loaded with checkout procedures that customize each station for a particular subsystem checkout. One console (Master) is responsible for managing the network, another (Integration) has the primary function of test integration.

Front End Processors (FEP)

The primary functions of the Front End Processors (FEP) are to acquire data from the Shuttle Vehicle and Ground Support Equipment, detect out-of-tolerance measurements, maintain current status of each measurement in the Common Data Buffer, notify responsible control stations and issue commands to the systems that are being tested. There are four types of

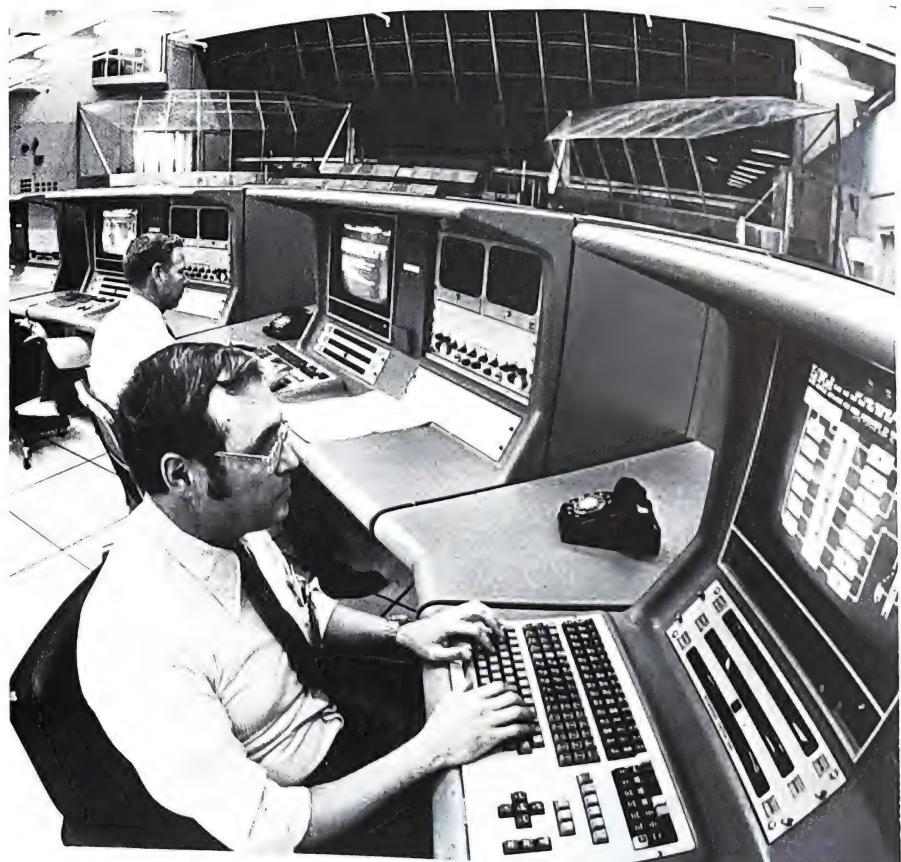


Figure 4. Test engineers at their LPS consoles.

Front End Processors:

- Pulse Coded Modulation (PCM)
- Ground Support Equipment (GSE)
- Launch Data Bus (LDB)
- Uplink

The PCM FEP receives telemetry streams from the Orbiter, decommodates it in accordance with pre-stored formats, and updates the Common Data Buffer with the most current value of each measurement.

The GSE FEP has a similar data acquisition function and, in addition, it controls a one-megabit ground data bus. Measurements are polled on a cyclic basis, via the data bus, ranging from one to one hundred times per second as defined by specifications contained in a Master Measurements data base.

The LDB FEP provides the interface of the LPS to the Orbiter's onboard avionics computer subsystem built by IBM. The FEPs respond to the onboard

computers just as does any other onboard system, i.e., the FEPs are polled cyclically by the onboard computers.

The Uplink FEP provides the capability to issue commands to the Orbiter via the communication and tracking network. This FEP formats commands from data obtained from internal tables and from the information supplied by requesting consoles and transmits these commands via the communications network. A type of uplink FEP is provided to read selected data from the CDBFR of interest to the NASA Marshall Space Flight Center at Huntsville, Alabama, and to transmit the data in real time to the Huntsville Operations Control Center.

Data Recording, Retrieval and Monitoring

The capability to record selected data that is being written to, or transferred across, the Common Data Buffer is

provided. The simultaneous logging of data to disk and tape provides the capability to play back, in near real-time, for analysis by test engineers. A time tag logged with accuracy within one millisecond of occurrence is appended to each transaction.

Hardware Interface Modules (HIM)

The HIMs provide the interface between the GSE FEP and the Ground Support Equipment such as the fuel pumps and other ground services to the Shuttle. The HIM converts digital data from the GSE FEPs to analog or discrete commands for the servicing equipment. The HIM is connected to GSE FEP via a one-megabit ground data bus. Measurements are also converted to serial digital data for transmission to the FEPs. Basically, HIM acquires measurement data and issues commands to GSE when requested by the FEP.

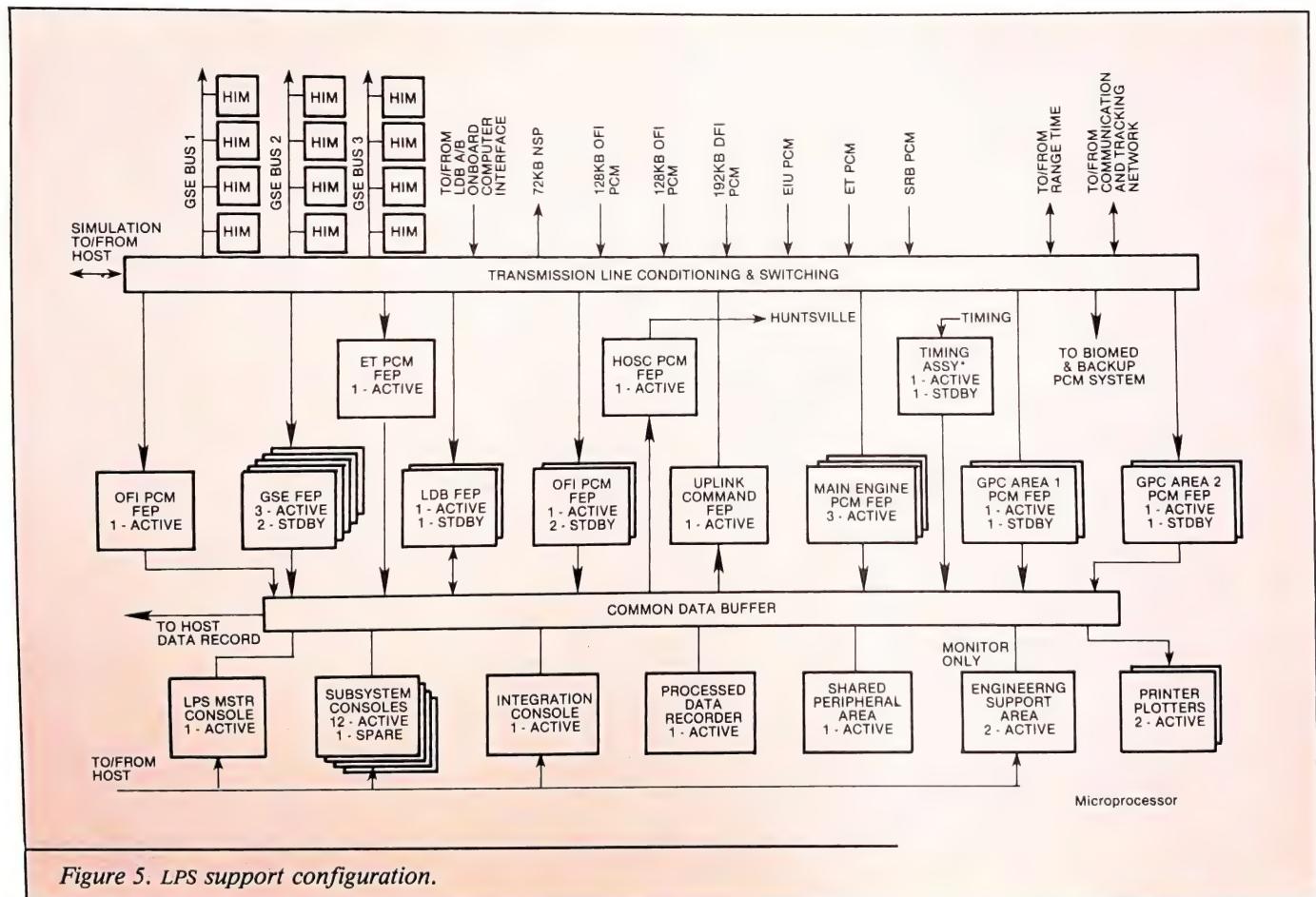


Figure 5. LPS support configuration.

Transmission Line Conditioning and Switching

The Transmission line conditioning and switching matrix provides the capability to connect a Firing Room to a specific set of items being tested. This capability allows the same test equipment to be connected to the Shuttle vehicle at any location during the checkout process, i.e., Orbiter Processing Facility, Vehicle Assembly Building, or launch pad. The subsystem also provides signal levels compatible with the data bus onboard the Orbiter and an interface to the host computer for simulated inputs to the networks.

The Host Computer

The types of functions performed on the host machine, two Honeywell 6680s, are data base management, high-level language compiling, and FEP table-builds.

The IBM-developed support software that runs on the host provides the user with the capability to build the test configuration that will be loaded into the minicomputer network. Elements of the support software include the high-level language compilers, data base management and FEP table-builds. The FEP tables describe measurements and commands, the Common Data Buffer (CDBFR) addresses, and PCM formats. The system-build process ties the user test program to CDBFR addresses, and formats the test configuration for loading into the minicomputer network.

The host machines are also used to record real-time data via an interface with the common data buffer. One machine can be configured to provide models of vehicle subsystems for use in program debug and verification prior to Shuttle testing.

LPS Architecture Summary

The LPS distributed minicomputer network has met the varied requirements of flexibility and high system availability. Redundancy management and reconfiguration techniques are key to the system's success. A number of techniques have been implemented throughout the system to assure command integrity (Figure 6). The data transfer across the CDBFR will be discussed later in the article to provide a better

understanding of some of the techniques implemented.

Redundancy Management and Reconfiguration

Management requirements of the redundant elements of the network created unique challenges to the LPS team. The backup computers had to be able to assume the active role in real-time with no loss of data. A switch of critical

In the protocol used to determine the operational status of network computers, each computer cyclically writes a health indicator to the Common Data Buffer. The health indicator consists of a status indicator and a counter. System Integrity monitors this health indicator and verifies the counter changes on successive cycles and determines status changes. When a computer's health counter does not change on successive cycles, the program

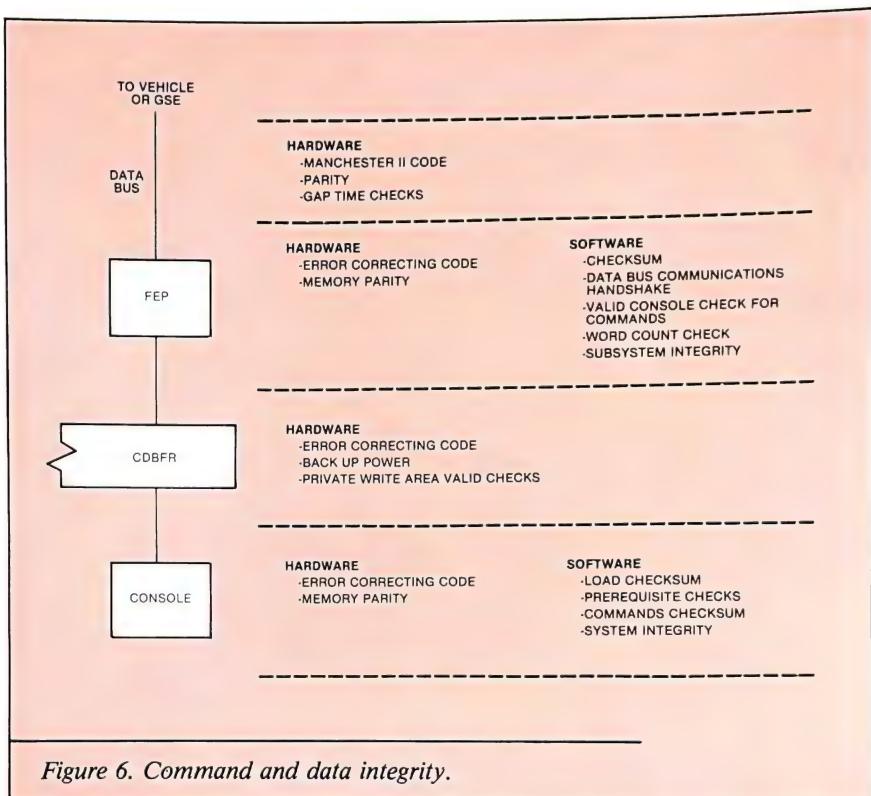


Figure 6. Command and data integrity.

function from one computer to another must be transparent to the test engineer. Data values in both active and standby units must be synchronized.

Failed Element Detection

A System Integrity program was developed to monitor the network computers and to control redundant computer switching. System Integrity consists of a monitor and control program which resides redundantly both in the Master and Integration Consoles and a slave program, called Subsystem Integrity, which resides at each network computer.

notifies each network computer that the computer is not operational. Health counters are monitored at 40ms and 500ms intervals. When an active computer of a redundant pair fails, System Integrity notifies each network computer that the system has switched to the standby computer. An active computer that detects a hardware problem, making it unable to perform its function, requests an automatic switch to backup by setting switch request status in the health indicator.

During the redundant switch process, computer-to-computer communications are redundantly managed to prevent loss of data.

Orbiter Interface Control A Special Case

The Launch Data Bus (LDB) FEPs control the LPS interface portion of a bidirectional data bus communication link to the Shuttle Orbiter Data Processing System. LPS uses this link to command the Orbiter system to initiate stimuli to end-items such as aerodynamic surface controls which are not under the direct control of LPS. Many

of these stimulus functions are of a critical nature upon which the safety of the Shuttle vehicle is dependent. In the prelaunch phase, the LPS is programmed to know when the stimuli functions are necessary. Onboard systems will not issue these stimuli automatically. Furthermore, there are no direct connections from ground control stations to Orbiter systems as was available in Apollo/Saturn systems.

All communications are transmitted

over digital data buses. Consequently, an LPS safety requirement is to maintain bus communication with the Orbiter despite any LPS single-point hardware failure. Any recovery time involved with a failure cannot exceed 500 ms. More importantly, no data loss is allowed on a single-point failure. In addition, the LDB FEP must honor bus requests from multiple LPS consoles concurrently.

To satisfy these requirements at the hardware level, there are two LDB FEPs, each with access to two launch buses (Figure 7). Any single FEP hardware failure or single bus failure will not perturbate LPS/Orbiter communications. A "vehicle safing" interface also exists as a backup to the CDBFR in the event that it fails. The LDB FEP may receive "safing" interrupts that request it to issue safing commands to the launch bus. These commands are predefined by the user and loaded into the FEP at LPS initialization time. The LPS user issues a safing command by physically throwing a "safing switch" located at an LPS console. This in turn causes the interrupt in the FEP as shown in Figure 7.

Handling A Single FEP Failure

The biggest problem encountered in satisfying the LDB redundancy requirement was that of handling a single FEP failure. Specifically those failures of the component variety such as memory parity, power loss, CDBFR communication channel failure, etc. The two LDB FEPs had to be "synchronized" in some sense so there is no data loss on single failure. However, the LDB FEP environment is not conducive to such an effort. The two LDB FEPs do not receive bus operation input requests from the LPS consoles simultaneously. Furthermore, the LDB FEPs do not have ultimate control of the launch bus. The IBM onboard system initiates the protocol that controls the proper flow of data on the bus in both directions. It was found during LPS development that the FEPs could not stay truly synchronized in this environment where not only the I/O events are asynchronous, but are non-simultaneous between the two machines.

The LDB FEP software was therefore augmented to include a "command

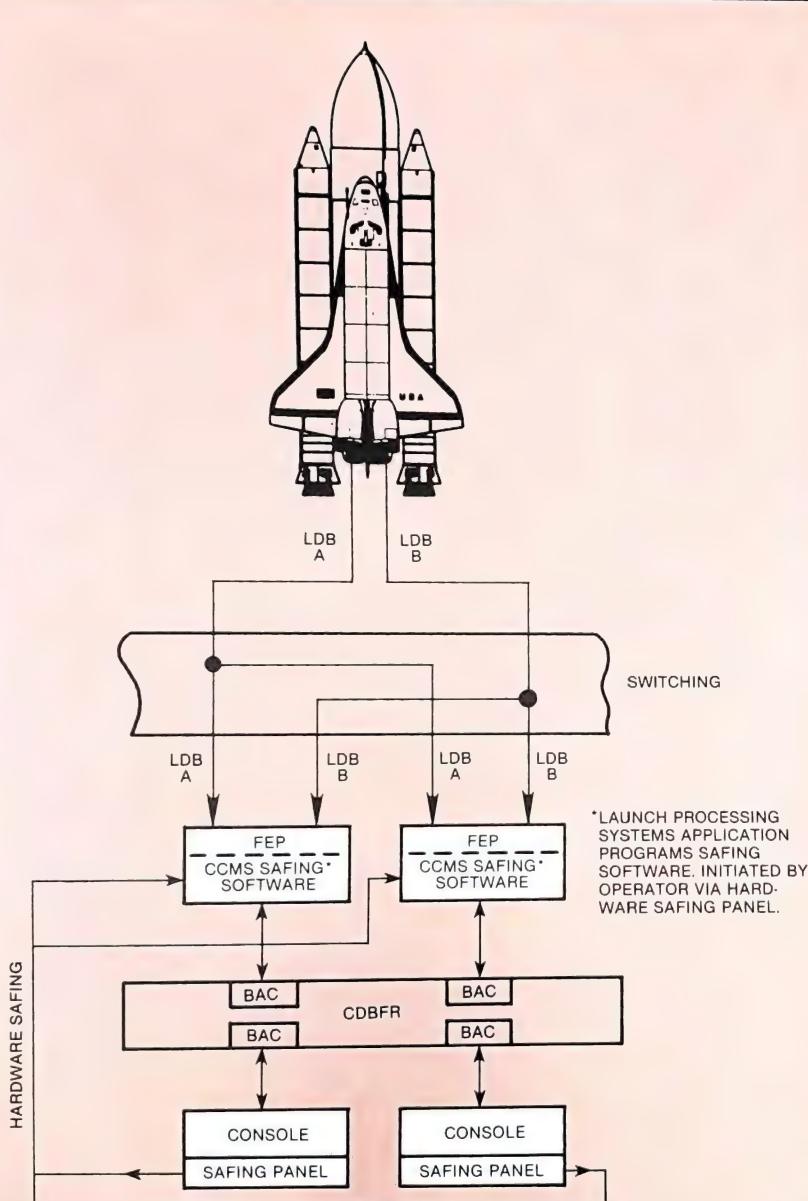


Figure 7. LPS application programs, safing software, flow diagram.

management" package. Software processes in the two FEPs are not identical; however, the internal state definitions of bus requests are maintained identically in the two CPUs. The internal states are basically defined as:

- a) requests pending bus uplink transmission
- b) requests transmitted and pending Orbiter bus downlink response.

The designated "active" FEP updates the "standby" FEP with changes to the bus request internal states in order to maintain the CPU redundancy. Only the active FEP actually transmits data on the bus and answers onboard protocol. The standby FEP does not transmit, but it does receive Orbiter data. The standby FEP does not detect uplink bus I/O events.

Except for some special-purpose launch data bus operations that are not critical, the LDB FEP software guarantees no loss of the data bus on an FEP failure, even if it is the active FEP. This protection even extends to the extremely unlikely cases where the active FEP fails between the completion of an I/O event and the reporting of that event to the previous standby, now to become active, FEP. The "new" active FEP has the capability to detect this single anomaly in the internal state definition of bus requests, and to continue bus processing correctly. The engineer's application programs are not perturbed on a "FEP switchover," except for an overall bus throughput time loss of approximately 300 ms.

Although the command management package only increased the LDB FEP-unique software size by 17 percent, the complexity of the software logic was significantly increased. The redundancy overhead lies in the more complex "control" aspects of the software, rather than the simpler aspects, such as command buffer formation.

Further protection is provided in the LDB FEP subsystem to allow for a "safing only" mode of operation (i.e., no CDBFR access) after a CPU power loss/restore. On the power restoration, the nucleus operating system software and the LDB FEP unique software purge all outstanding operating system data, re-establish all essential software queue structures, and re-enable the vehicle safing and launch bus transmitter/receiver interfaces. Orbiter safing commands may be subsequently up-linked to the launch data bus via the vehicle safing mechanism described previously.

There has not been a single point failure in the LDB FEP subsystem in an operational environment during a major Shuttle test. However, repeated LDB FEP tests in which single failures were induced substantiate that the software does indeed maintain the proper launch bus communication with no data loss.

A Fault Tolerant Example

The common data buffer is the heart of the LPS, but could not be practically implemented in the conventional active/backup approach to high availability. Therefore, the system was implemented to be fault tolerant. Custom microcode was developed for the common data buffer interfaces and it plays a key role in the fault tolerant system.

The computer-to-computer communication scenario (Figure 8) is described to explain the fault tolerant characteristics of the common data buffer.

Integrity of the Buffer is also protected during commercial power failures by providing it with uninterrupted power. In the event of a facility power loss, batteries that are maintained on-line will provide power for enough time for diesel generators to start. Tests performed demonstrated no perturbations to system operations due to power switchover.

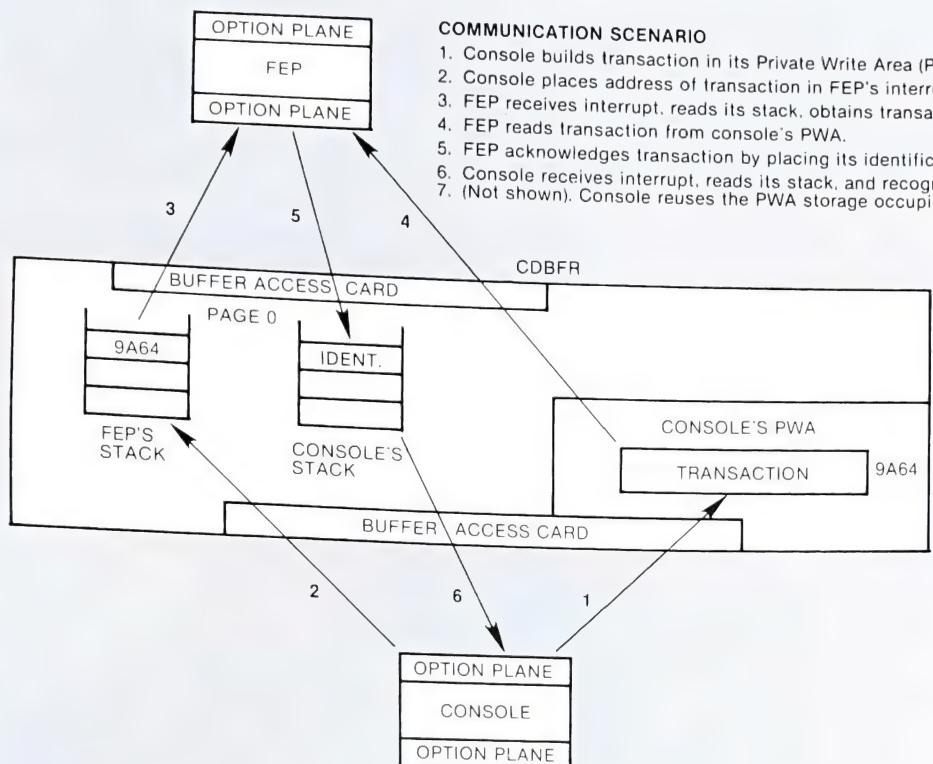
Summary

Support to one launch does not constitute total success for the LPS. However, data from the launch of STS-1 indicated safe margins for planned NASA and DoD launches (Figure 9). The challenge for the future is to provide the user with better tools to further automate the checkout process, assist in customizing application procedure for each launch, and streamline the system-build process to expedite the installation of mission-unique changes.

Development is currently under way to add a secure communication capability to the LPS to meet DoD requirements and to add enhancements to assure the system will meet the challenges of new payload checkout.

Today, nine LPS systems are operational with three additional planned for the future (Figure 10).

Overall, the concept of a closed loop control system implemented by a systems network made up of commercially available minicomputers has been clearly demonstrated. Hardware, software and microcode techniques can be implemented to assure system data integrity and high system availability. (See pages 24 and 25 for Figures 8, 9 and 10.)



Sending

The sending CPU formulates a message with a corresponding check-sum. This message is written to the Buffer in its Private Write Area (PWA). All data written to the Buffer is transferred by the sending CPU's Buffer option plane. The option plane generates a 16-bit Error Correction Code (ECC) word (for error detection and correction) for each 16-bit word transferred to the Buffer. The option plane sends the Buffer address, its corresponding ECC word, datum to be written, and its ECC word to the Buffer Access Card (BAC). Data ECC is transmitted over the address line and the address ECC is transmitted over data lines. This switch of ECC precludes some hardware failure from perturbing data or address and accompanying ECC. The BAC places these four words on the bus

where the address and data are checked (and corrected if possible). The address is verified to be within the limits of the sending CPU's PWA and, if all is valid, the data and its ECC are written into the Buffer memory. After the sending CPU has written the complete message in its PWA, it then writes the address of its PWA into the stack of the receiving CPU.

The Buffer detects this input to the receiving CPU stack and generates an interrupt to the receiving CPU. The receiving CPU reads the address from its stack to determine where to read the message. All data read from the Buffer is transferred through the receiving CPU's CDBFR option plane. The option plane sends the address and address ECC to its BAC, requesting a read. The BAC places this address

on the bus where the address is checked and corrected if possible.

Receiving

If all is valid, the read is performed and the read data and its ECC are sent to the receiving CPU's BAC. The receiving CPU then can read the data and its ECC and check the data for validity, correcting any correctable errors. After reading the address of the message from its stack, the receiving CPU can then read the entire message from the sending CPU's PWA. The receiving CPU does a check-sum of the message to compare to the check-sum generated by the sending CPU as a further data validity check. Any acknowledgement necessary is returned to the sending CPU in the same manner as the original message was sent.

Figure 8. Computer-to-computer communication example.

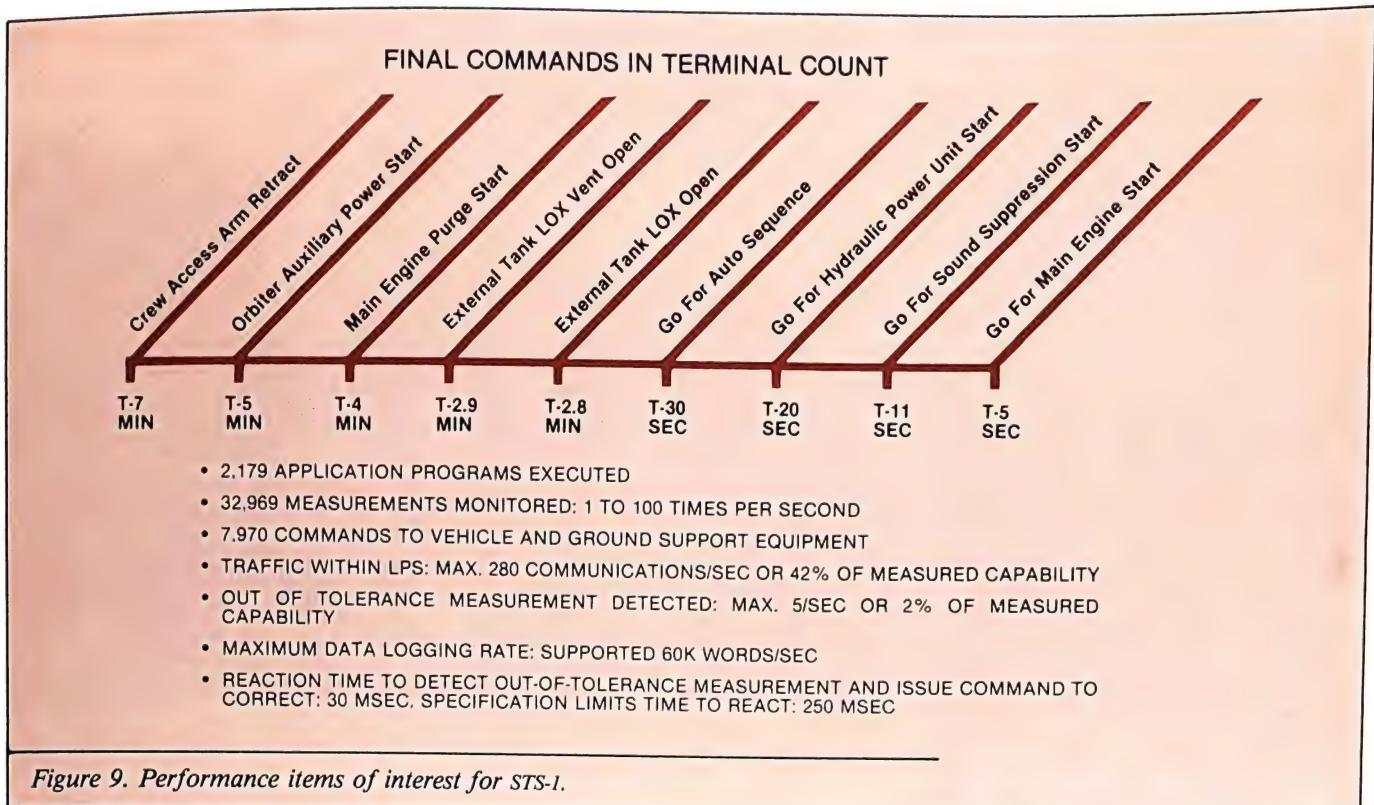


Figure 9. Performance items of interest for STS-1.

LPS SETS				
Name	Location	Computers	Status*	Function Performed
Firing Room 1	CKF	41	O	Support Launches
Firing Room 2	CKF	27	O	Back up to FR-1 for RDT&E Launches Application Procedure Development Laboratory
Firing Room 3	CKF	35	P	Support Launches Secure Communication Capability
Shuttle Avionics Integration Laboratory	JSC Houston	8	O	Ground/Onboard Avionics Integration Vehicle Application Procedure Debug and Verification
Serial #0	CKF	14	O	System Software Development and Integration
Hypergolic Maintenance Facility	CKF	5	O	Shuttle Major Electromechanical Subsystem Refurbish and Revalidation
Complex Control	CKF	12	O	Control of facilities such as water, electrical power, air conditioning, sound suppression
Cargo Integration Test Equipment	CKF	9	O	Orbiter/Payload Interface Verification prior to inserting in Shuttle
North Vandenberg	VAFB, Calif.	24	O	AF Application Procedure Develop Operationally support Orbiter Refurbish/Revalidation
South Vandenberg	VAFB, Calif.	34	P	Control launches from Western Launch Site
Solid Rocket Booster	CKF	9	O	Solid Rocket Booster Avionics Checkout prior to stacking
Orbiter Function Simulator	ETR	2	P	Orbiter Interface Verification of DoD Payload-Payload and Operation Control Center Interface

* O = Operational
P = Planned

Figure 10. Distribution and future plans for LPS locations.

The Operational Control System for the Global Positioning System

by James J. Selfridge

The Navstar, Global Positioning System (GPS), scheduled to become operational in the mid-1980s, is a space-based radio navigation system which provides position and velocity accurate to less than 16 meters and 0.1 meters, respectively, per second to users anywhere on the globe in any weather, day or night.

The system is composed of three segments. The Space Segment (Figure 1) consists of 18 satellites, each one of which continuously radiates a signal containing the satellite's precise position and an absolute time reference related to a highly accurate onboard clock. The User Segment, planned for both military and civilian needs, aircraft pilots, ship captains or field com-

bat soldiers, uses special-purpose, passive (receive only) receivers, and computes exact, three-dimensional position and velocity from the signals of four or more of the satellites. The Control Segment monitors the position of each satellite and the conditions of their onboard clocks and uses this information to periodically update each satellite with current position predictions and absolute time corrections.

The GPS is being developed by the Space Division of the U.S. Air Force Systems Command for the Department of Defense. DoD sees GPS initial costs for the military alone, over the next 20 years, as being less than what it would cost to upgrade or replace today's existing radio navigation systems (LORAN,

OMEGA, TACAN, and other similar systems). Performance of GPS was proven during the Concept Validation Phase conducted from 1977 through 1979. In meeting all performance measures, GPS demonstrated 10 times greater accuracy in navigation and four times more accuracy in weapons delivery over other current or planned systems. Net cost benefits from the use of GPS is seen as approximating \$57.6 billion.

The cost of providing an equivalent military capability without GPS is \$59.7 billion and the cost of maintaining current radio navigation systems is \$3.3 billion. The initial cost of GPS is \$2.9 billion and operations and maintenance costs through the year 2002 are \$2.5.

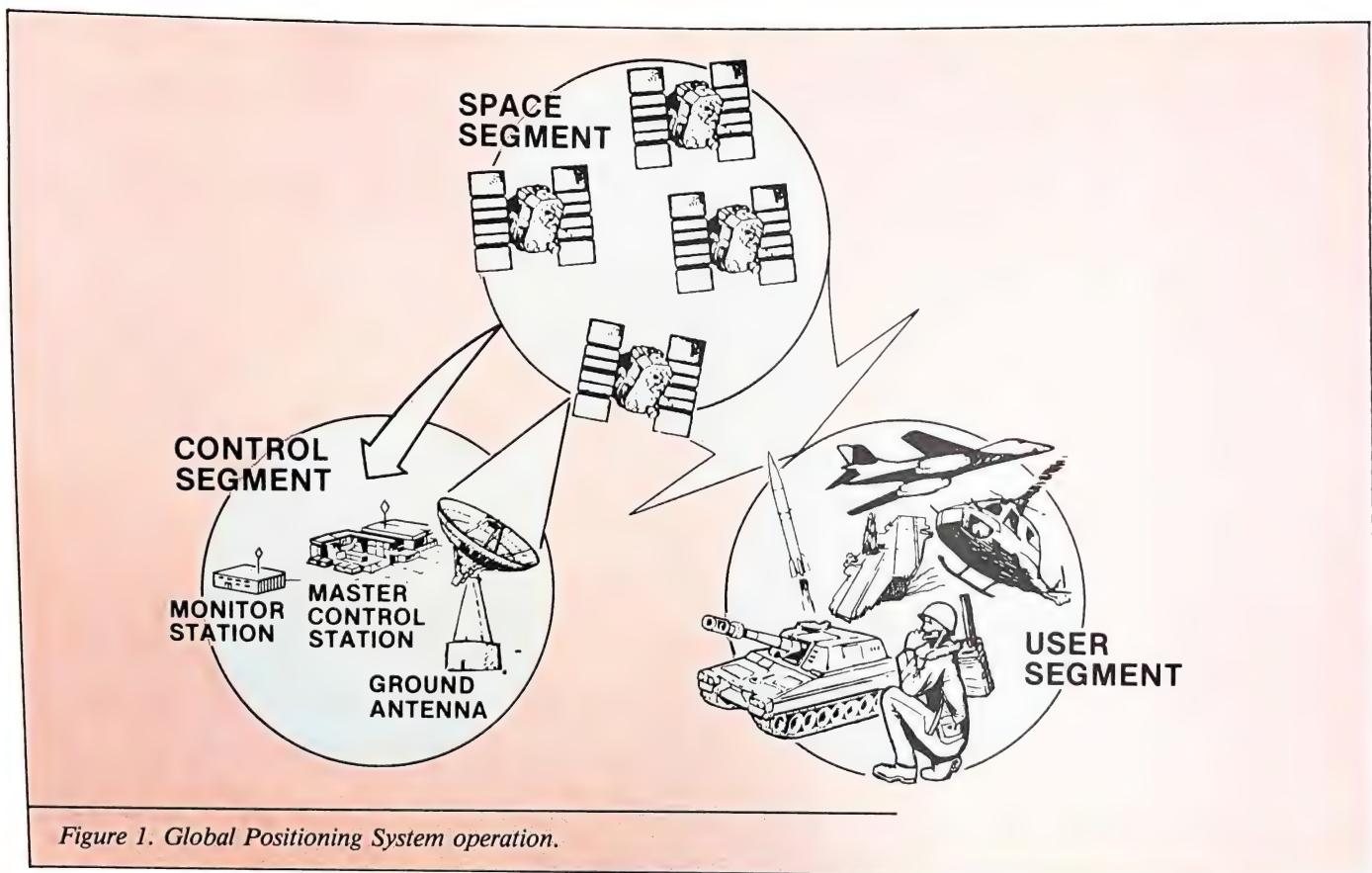


Figure 1. Global Positioning System operation.

Thus, the net cost benefits from the use of GPS is seen as approximately \$57.6 billion.

Potential benefits to the civil community are typified by the GPS revolutionary impact on military missions. Air traffic control, to cite one civil application, could be safer with higher density through the precise positioning available with GPS.

The IBM Federal Systems Division's (FSD) facility at Gaithersburg, Maryland, has prime contractor responsibility for the GPS Control Segment, also known as the Operational Control System. To achieve system accuracy, the IBM-developed ground facilities will periodically measure each satellite's precise location, predict its position between contacts, calibrate the atomic clocks on board the satellites and provide new navigation signals to the satellites. As part of the Operational Control System, IBM is providing a Master Control Station to be located in the central continental United States; five Monitor Stations to be distributed globally at surveyed sites to collect the satellite navigation signals; and three Ground Antennas also distributed globally to periodically update the satellite's navigation data and to command the satellites based on satellite telemetry.

IBM's responsibilities include design, specification, development, installation and test of all IBM-supplied hardware and software, and the complete responsibility to integrate the IBM-supplied components with government furnished equipment and facilities. In addition, IBM ground equipment must provide an RF interface to the satellites for uploading data and collecting signals. All software used in the system, including that used to generate the satellite position and time estimates uploaded to the satellites and radiated from the satellites to the user, has been specified by IBM as have the system manning requirements for operations and maintenance.

The Operational Control System software, which integrates all requirements, represents the single most significant challenge to the successful development of the GPS system into a reliable military support system, easily operated by available military personnel.

The Operational Control System contract was initiated with IBM in Sep-

tember, 1980. The full capabilities of the system will be implemented in the fall of 1985. During the U.S. Air Force Initial Operations and Test Phase, which lasts through early 1987, IBM will provide training and integration support to the Air Force. Twelve subcontractors support IBM on the program, including the Harris Corporation for Ground Antennas, Stanford Telecommunications, Incorporated for Monitor Station receivers and the OAO Corporation for operations.

The Space Division Joint Program Office for GPS development includes personnel of the U.S. Navy, U.S. Army, U.S. Marine Corps, the Defense Mapping Agency, Department of Transportation and nine NATO countries. GPS is now in full-scale engineering development and test, having completed the concept validation program in mid-1979. During the concept validation, 775 test objectives were met. These included tests to demonstrate navigation accuracy, threat performance (e.g. jamming), environmental effects (e.g. multipath, foliage attenuation, helicopter rotor modulation), and system characteristics of satellite clock and ephemeris accuracy, signal acquisition time, time transfer and signal levels and structure.

IBM is currently maintaining and operating the Phase I Control System at Vandenberg Air Force Base in California. The Phase I Control System, developed to support the GPS concept validation testing, consists of a limited satellite ephemeris and clock offset computation and upload transmitter facility at Vandenberg with four preliminary monitoring stations located at Vandenberg, Guam, Alaska and Hawaii. The U.S. Air Force Satellite Control Facility provides satellite telemetry and command capability prior to Operational Control System implementation. An Initial Control System (ICS) will be installed at Vandenberg in by mid-1982, it will replace the Phase I System. The ICS will provide capability for an increased number of satellites over the Phase I Control System and will use one of the IBM 3033 computers to be installed in the Operational Control System. This paper briefly describes the navigation signal and the three GPS segments and discusses the significant design trades and features of the Optical Control System.

Navigation Signal

The baseline constellation of 18 satellite vehicles (SVs) operates in near circular orbits of 10,898 nautical miles, at a 55-degree inclination and with 12-hour periods. Since the GPS Satellite Vehicles are continuously radiating the navigation RF signal, users can obtain precision navigation data at any time, under all weather conditions and at any latitude, longitude or altitude. Depending on their geographic location, users will be able to receive RF signals from between four and seven SVs of the 18 in the constellation. Each user determines its own position by measuring the transit time of the radiated navigation signal from any four SVs in view of the 18 satellite constellation. User accuracies on the order of 16 meters in position and 0.1 meters per second in velocity are planned.

Three SVs are needed to compute position, four SVs are needed to obtain time relative to the U.S. Naval Observatory Universal Time Coordinated (UTC) to 0.1 microsecond. Signals are transmitted from the SVs on two L-Band frequencies (L1 at 1227.6 MHZ and L2 at 1575.42 MHZ). The use of two frequencies permits corrections for ionospheric delay in signal transit time. Each L-Band frequency is modulated by pseudo random noise (PRN) codes and each L-Band frequency is further modulated by the navigation message. The PRN codes are the clear/acquisition (C/A) code at a 1.023 MHZ rate and the Precision (P) code at 10.23 MHZ. The C/A code is a 1023 bit Gold Code, with a unique code for each satellite. The code repeats each millisecond while the longer P Code repeats every 267 days. Each satellite is assigned a unique one week section of the long P code. Each P code section is reset to its initial value weekly.

The 1500-bit navigation message frame (Table 1) is divided into five equal subframes and contains the satellite ephemeris data, the satellite clock offset data, and a subcommunicated almanac of summarized position date for all satellites in the constellation. One word of each frame contains the almanac data for another satellite vehicle in the constellation. To obtain the complete almanac requires 25 frames of data. The navigation message also contains other informa-

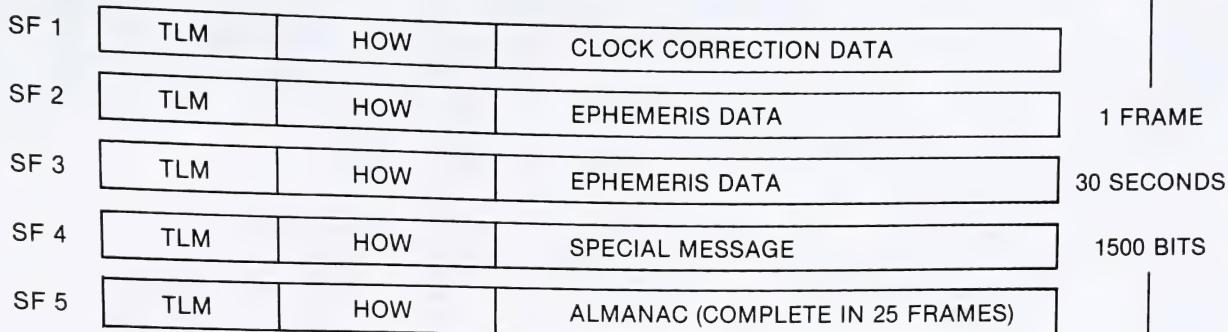
Table 1. Navigation Signal and Data

PARAMETER	C/A SIGNAL	SIGNAL
Code Rate	1.023 Mbps	10.23 Mbps
Code Period	1.0 Second	~267 Days, Reset Weekly
Data Rate	50. bps	50 bps
Transmission Frequency	1227.6 MHZ	1227.6 MHZ, 1575.42 MHZ

DATA FORMAT, FRAME/SUBFRAME STRUCTURE

EACH SUBFRAME (SF) = 10, 30 BIT WORDS

EACH SUBFRAME = 6 SECONDS



tion, such as the telemetry word (TLM) used by the control segment and user equipment for control and status. The navigation message is transmitted at 50 bits per second, repeating every 30 seconds. Each six seconds, at the beginning of each subframe, a Hand-Over Word (HOW) occurs. The HOW contains a count which allows a user to acquire the higher level, more accurate P code directly after the user has acquired the relatively short C/A code.

The Space Segment

The 18 satellites noted above with six spare SVs comprise the Space Segment. Each SV contains a Navigation Data Unit which includes control and storage for SV position data, atomic clocks, signal generation and modulation equipment. SV position data and satellite clock correction data uploaded to the

satellite by the Operational Control System are transmitted as the navigation message and modulates the L-Band signals in addition to the P and C/A code modulation. Predictions of the satellite ephemeris and clock calibration function are generated by the OCS for application hourly on the first day, then on successive four-hour periods for the next 13 days. The SV ephemeris is a set of parameters which precisely describe the SV orbital position referenced in time to earth coordinates.

Each data upload is a full 14-day message of approximately 192,000 bits although each SV will receive newly computed inputs three times daily. The satellite Navigation Data Unit gates and transmits the stored message on time. In the event that data uploads do not occur, the satellite automatically provides data with gracefully degrading accuracy over 14 days.

Precise timing of the satellite transmissions is controlled using the atomic clock signals. Each SV has four atomic clocks, two Cesium and two Rubidium Frequency Standards and subsystems for electrical power; control of attitude, velocity, reaction, temperature, telemetry and command; and RF equipment for receiving and transmitting. The SV electrical system batteries are kept charged by solar panels. The attitude and velocity control subsystems and the reaction control subsystem properly maintain the SV in the constellation. Louvers and heaters actuated by the thermal control subsystem cool and heat the subsystems. Operational Navigation Satellites, (ONS), which have a six-year mean mission duration and a 10-year consumable supply, will be launched by the Space Transportation System Space Shuttle. Each Shuttle will launch from one to four satellites using

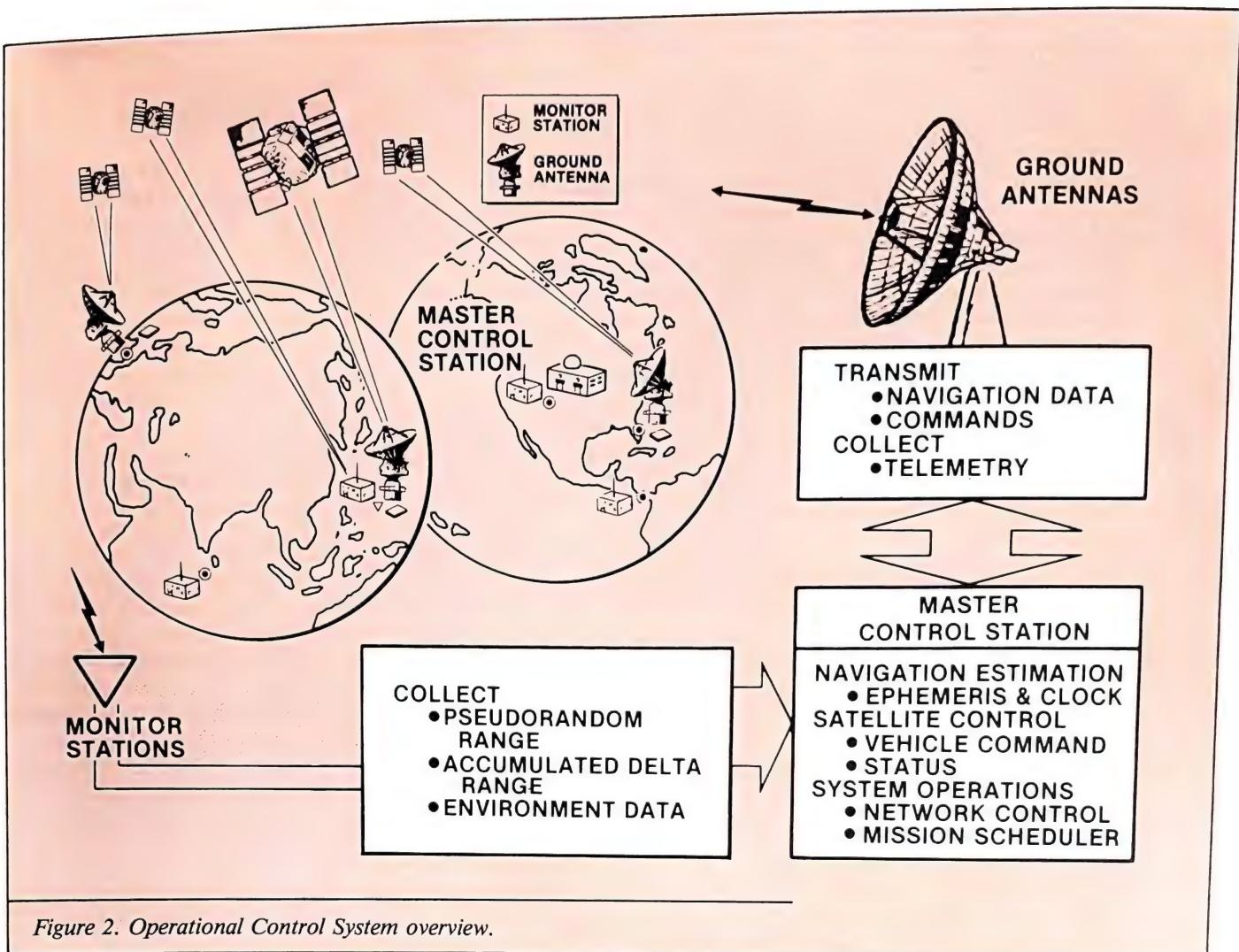


Figure 2. Operational Control System overview.

the Payload Assist Module D (PAM-D). The ONS Navigation subsystem is protected against spoofing and cosmic ray upsets. Satellite survivability measures include command and upload encryption and protection from laser, jamming and nuclear threats.

User Segment

The User Segment is extremely broad and provides for civilian as well as military applications. Users may be any suitably equipped aircraft, ship or surface vehicle as well as space vehicles and man-packs. Military applications include tactical and strategic reconnaissance, rendezvous, targeting and weapons delivery. Potential civilian applications are air traffic control, ship navigation, oil exploration and geodesy. High dynamic aircraft may have multiple antennas to collect the RF

signal from the SVs while maneuvering and may have multiple receiver channels to compute positions to meet the real-time mission needs. GPS User Equipment is comprised of four principal components; including an antenna, receiver, processor and input/output units. Receivers may be single channel which recover and process one signal at a time, sequentially processing multiple satellite signals; or receivers on a high performance aircraft may have up to five channels processing five P signal pairs simultaneously from up to five satellites.

The receiver usually performs data detection and carrier tracking and filtering. The computer functions include receiver control, selection of satellites and signals to be used, correction of measurement data for propagation effects, computation of position, velocity and time, and calibration of the

receiver. Inputs to the computer may include approximate satellite positions, time and vehicle altitude and attitude to aid in signal acquisition. Output from the GPS set may drive a display, or aid a vehicle control unit or weapons direction unit.

Control Segment

Figure 2 provides an overview of the Operational Control System (OCS) and the major functions of its subsystems. The Monitor Stations (MSs) are unmanned data collection subsystems which operate under control of the Master Control Station (MCS). Tentative locations for the Monitor Stations include Diego Garcia in the Indian Ocean, Ascension Island, Guam, Hawaii, Eastern Launch Site and the OCS MCS in Central U.S. Each Monitor Station can have up to 12 two-channel receivers

which collect the L1 and L2 navigation signals from each satellite in view. (Note: The OCS is designed to accommodate satellite growth to 24 active and eight spares from the 18 active and six spares in the current baseline. With 24 satellites as many as 10 could be in view of a Monitor Station at one time).

Tracking measurements from the L1 and L2 signals, including pseudo range, accumulated delta range and signal strength, are transmitted each 1.5 seconds to the Master Control Station. Local meteorological measurements are also sent to the Master Control Station to compute a tropospheric correction. Two Frequency Standards, commercially available atomic clocks, provide a local reference time and provide data to the Master Control Station on Monitor Station clock stability. The Navigation Data Message coming from the satellite at 50 bits per second is collected at the Monitor Station and forwarded unmodified to the Master Control Station. Data can be stored for up to five minutes at the Monitor Station to buffer communications outages.

Three Ground Antennas (GAs) located around the world provide an S-Band communication link with the satellites for telemetry data collection, satellite commanding and navigation data uploading. GAs will normally operate under direct control from the Master Control Station receiving and transmitting signals, however, navigation messages will be prestored one hour prior to upload and may be sent under local direction using the maintenance console at the GA site with voice coordination from the Master Control Station in an emergency backup mode.

The Master Control Station (MCS), which will be located at the Navstar Operations Center provides overall control of the GPS system. The NOC includes the Master Control Station, the co-located Monitor Station, and Personnel subsystem (PSS). A loosely coupled duplex IBM 3033N8 computer with specially designed interactive consoles support mission operations personnel. One or the other of the 3033N8s is designated as the primary or active processor. It performs time critical functions of the ephemeris and clock computation for the navigation mission and SV control and status under supervision of the personnel in Mission Operations. Processing of critical func-

tions can be provided by the backup or passive processor within 60 seconds if the active processor fails. The passive processor normally performs the less time critical functions of SV positioning for orbit maintenance, data base/software maintenance and training.

Data Communications between subsystems of the OCS is provided through dedicated voice grade communications circuits. Monitor-to-Master Control Station communications require 4800 baud service; Ground Antenna to Master Control Station communications require links of 9600 baud service to accommodate telemetry rates. Terminal support for voice, facsimile and telegraphic communications are also included in the design.

The OCS was designed to facilitate 24-hour-a-day operation with a small operations and maintenance crew with on-call specialists. The shift operations crew at the (MCS) (Figure 3) has three Pass Controllers to provide for three simultaneous OCS/SV contacts.

The OCS Design Process and Subsystem Descriptions

IBM was awarded the contract to develop the OCS as a result of a competitive design study which began in January 1979 and was completed with IBM's selection for contract negotiation in July 1980. During the competitive design, numerous analytic tasks and trade studies in system engineering, hardware, software and system test and integration were performed. The following sections describe some of these studies and analyses and provide additional design detail.

System Engineering and Architecture

The OCS must meet a number of requirements in accuracy, SV protection, processing capacity, autonomy of operation, SV prelaunch testing, various telemetry rates, built-in test and maintenance capability, and scheduling of the OCS itself. The driving performance requirements on the design are as follows:

- (a). support a total navigation error budget of < 6 meters measured as user range error (URE).
- (b). provide at least one SV contact each eight hours to maintain SV health.

(c). satisfy an OCS Mission Availability (MA) of ≥ 0.98 where

$$MA = \frac{\text{Total No. of Contacts} - \text{Missed Contacts}}{\text{Total No. of Contacts}}$$

URE is defined as the error component along the line of sight between a user to the SV being evaluated. The navigation error budget is based on a SV clock with frequency stability of one part in 5×10^{12} over 28 hours. The OCS maintains the navigation error in bounds by continuously collecting satellite radiated navigation data at the Monitor Stations, generating new ephemeris and clock offset predictions for each SV as often as necessary each day at the Master Control Station and uploading the new ephemeris and clock correction data through the Ground Antennas.

The algorithms, parameters and frequency of the computations should minimize the errors due to the instability of the SV clocks, unmodeled forces acting on each SV, and inaccuracies in the OCS data collection, measurement and computation process itself. Modeled forces acting on the SVs include earth mass, solar gravity, lunar gravity, solar radiation pressure and gravity anomalies.

Providing accuracy in position and time is the most important function of GPS. Therefore, the analysis and design trades associated with accuracy received the highest priority during the design study. An experimental measurement station was built to collect measurement data to validate Monitor Station receiver design characteristics. In addition, a stationary navigation process control system software module was programmed on an IBM System/370 computer. Data were collected by the measurement station, processed through a model of the smoothing program, fitted to a Reference Trajectory obtained from the Naval Surface Weapons Center (NSWC) and used to predict an SV ephemeris. Then a navigation message suitable for upload was generated. When compared with the "truth" model from NSWC the Root Mean Square (RMS) errors were 7.3 meters. This result was surprisingly close considering the use of only one measurement station and of an estimated SV force model in the computations.

Extensive adaption of the TRACE Program developed by the Aerospace

Corporation provided a capability to analyze clock error propagation, monitor station site locations, and to perform a sensitivity analysis highlighting design issues affecting accuracy. Table 2 summarizes the results of this analysis. While the SV clock instability has the most effect on system accuracy, the OCS is designed to overcome these effects with the Monitor Station receiver measurement, the navigation message upload strategy and GA site locations. Accuracy effects due to the number of Monitor station sites is low; however, the design provides five stations globally to detect SV signal anomalies which could provide an indication of more serious SV problems. Monitor Station coverage of the available SV signal masked below 5 degees for five potential Monitor Stations is shown on Figure 4. Signals can be collected almost 95 percent of the time. Signal collection coverage is centered about each Monitor Station

location. In addition to accuracy considerations, GA site locations were affected by a need to assess the status of the electrical power system on the prototype SVs at least once every eight hours.

Mission availability requirements of > 0.98 were met for the system by considering the loss of components of each subsystem. Monitor Station equipment is not redundant since the system can operate for short periods without all Monitor Stations or their channels. However, to improve Monitor Station availability and reduce station maintenance requirements, dual Frequency Standards are used, receiver channels will be programmable, and several receiver channels can be out before repairs are necessary. In the event of a GA/Master Control Station communication outage, the GA will have the capability to store telemetry until restoration and to restore contingency input data for autonomous

upload up to one hour prior to transmission to avoid missed SV contacts. The Master Control Station design, with its duplex processors, will have cross strapped I/O, GPS mission software allocated to processors on an online or deferrable basis and a one minute switchover between processors.

Risk reduction across the system was achieved by the use of off-the-shelf computers, operating systems, real time executive and the selection of the Synchronous Data Link Control (SDLC) protocol for data communication. The message block size for data communication between the Master Central Section and the Monitor Station and between the Master Control Station and GA was selected to meet the capabilities of the 10^{-5} BER circuits provided by the government.

Life cycle costs considerations resulted in the selection of commercial equipment and software whenever possible. The Master Control Station

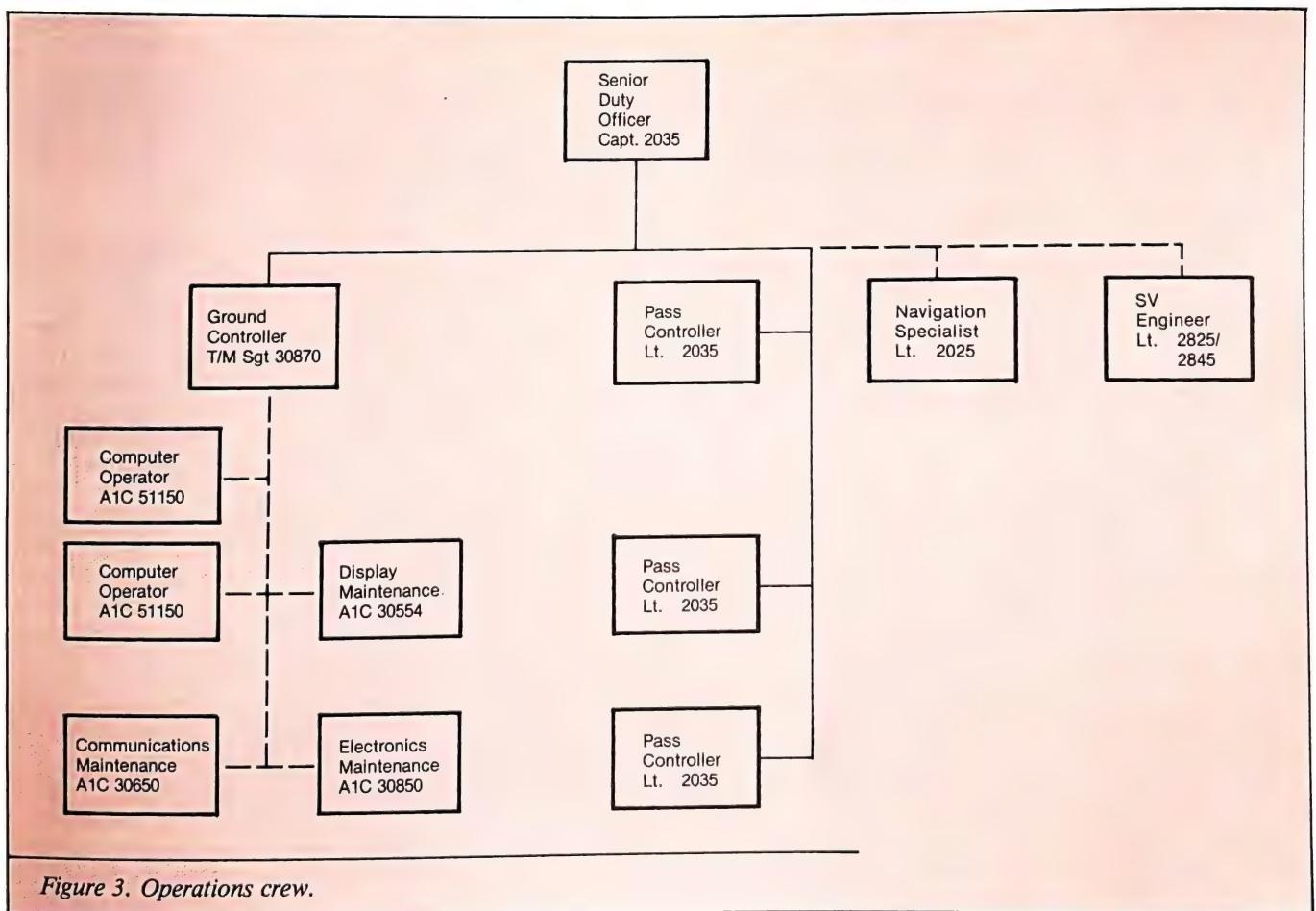


Figure 3. Operations crew.

Table 2. Summary of Sensitivity Analyses

Sensitivity Investigation	Importance to System	Comment
1. Number of MS	low	
2. Location of MS	high	
3. Kalman Sampling Interval	low	critical function in conjunction with continuous coverage, multiple uploads and end point filter
4. Elevation Mask	low	
5. Number of Partitions	low	
6. Fit Interval	low	
7. Relative PR to ADR Weighting	moderate	should exceed 36 hours
8. Type of Clock Estimator	low	ADR needed at MS to give low PR sigma
9. Staggered Upload	high	linear, end point for ONS clocks
10. Integration step size	low	implications relative to stated accuracy
11. Degree/Order of Grav. Field	low	
12. Constellation	low	
13. Number of Uploads vs No. of GAs	high	2 or 3 uploads with 2 GAs, 4 uploads with 3 GAs
14. Error Contribution		
a. Random PR	low	
b. Master MS	moderate	HP 5061A (004) Cesium acceptable
c. Other MS	low	based on use of HP 5061A (004)
d. SV clocks	high	dictates achievable accuracy
e. Consider parameter	low to high	depends on definition of accuracy and system tuning
15. Number of receivers per MS	moderate	influences elev. mask and repair strategy

will use the Command Control System, Control portion from the NASA Shuttle program as the real time executive. The Monitor Station and GA will use the same real time executive program. Unmanned operation of the Monitor Station and GA reduced overall manning needs. The capability designed into the MCS software and the display design allow the use of currently available skilled personnel in the Air Force.

Operations Concept and Personnel Subsystem

To formulate the Operations Concept and Personnel Subsystem all of the activities necessary to support the Navigation Mission and the satellites were defined. Each requirement, e.g., satellite anomaly, ephemeris and clock prediction, data collection, etc., was analyzed and allocated to one of the OCS subsystems. The allocated requirements were then expanded to determine the

frequency of occurrence, the criticality and the operator's role in satisfying the requirements.

SV support requirements, key to the GPS mission, received particular attention. Navigation upload frequency, based upon accuracy requirements, normal orbit maintenance of the SVs and potential contingency situations were analyzed to establish the daily/hourly SV support requirements. A SV Activity Summary, considered in the analysis, is shown in Figure 5.

Integrated timelines were developed which were the result of apportioning the OCS activities over a typical 24-hour period. Included were many normal and contingency mode scenarios.

In developing the personnel subsystem, the timelines were analyzed along with OCS support activities to determine the number of personnel and the skills required to accomplish the mission. Existing Air Force skills were studied as were existing organizations

(Defense Support Program, Defense Meteorological Satellite Program) whose operations centers are similar to GPS. Minimizing the number of personnel without sacrificing system effectiveness was a principal consideration to achieve low life cycle costs.

The Personnel Subsystem consists of 85 airmen and 66 officers, was defined and requires current Air Force skills. The command structure, (Figure 6) allocates responsibilities to the Mission Operations crew and the support branches.

Monitor Station Design

The most significant Monitor Station design consideration was the collection strategy for L1 and L2 signal measurements from each SV to be selected for the Kalman Filter. The signal measurement process was considered the first half of a total selection process which includes the data editing, correcting

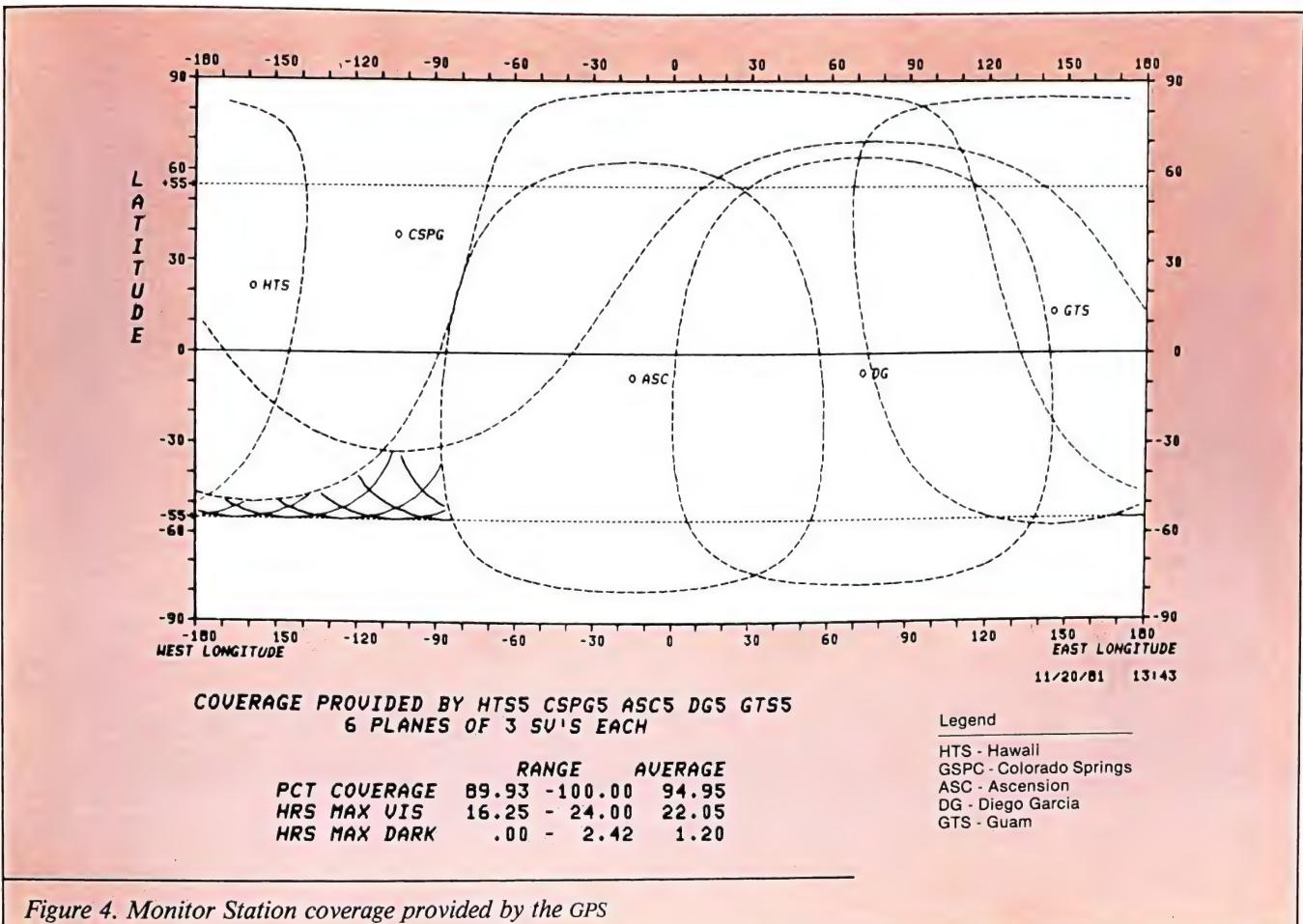


Figure 4. Monitor Station coverage provided by the GPS

and smoothing prior to use of the Pseudo Range (PR) data in the estimation process. The measurement of range to the SV calculated from the signal transit time is called Pseudo Range since it contains bias errors due to SV clock and position uncertainties as well as other uncertainties. Analysis showed that the use of PR with Accumulated Delta Range (ADR) (equivalent to integrated Doppler) to aid in smoothing the Pseudo Range results in a superior measurement product. This technique devised by IBM provides the optimum in error reduction, eliminates the introduction of bias terms and results in a significant reduction (600 to 1) in computation time in the edit and smooth process. The technique requires a receiver to track ADR on both frequencies continuously and to track PR and ADR to within a constant bias. Such a receiver was built to IBM specifications for the experimental measurement station during the GPS

design study and demonstrated that the ADR measurements have the desired properties.

The stations will be unmanned and operate automatically under control of the Master Control Station. Monitor Stations will be located in secure facilities at DoD bases. Maintenance will be provided through the host base on an on-call basis. As a result, the Master Control Station will be the capability to exercise and test the Monitor Station equipments (Figure 7) and isolate failures, and the station itself is designed for simplified maintenance. For example, each receiver channel will always track an SV or a test signal generator so that failures can be immediately detected; channels will be assigned to the test signal generator to monitor absolute drifts prior to and just after tracking; and idle time on receiver channels can be assigned as duplicate tracking channels to the same SV. The ground controller at the Master Control Sta-

tion is alerted to channel and station drifts as well as data which exceeds limit checks.

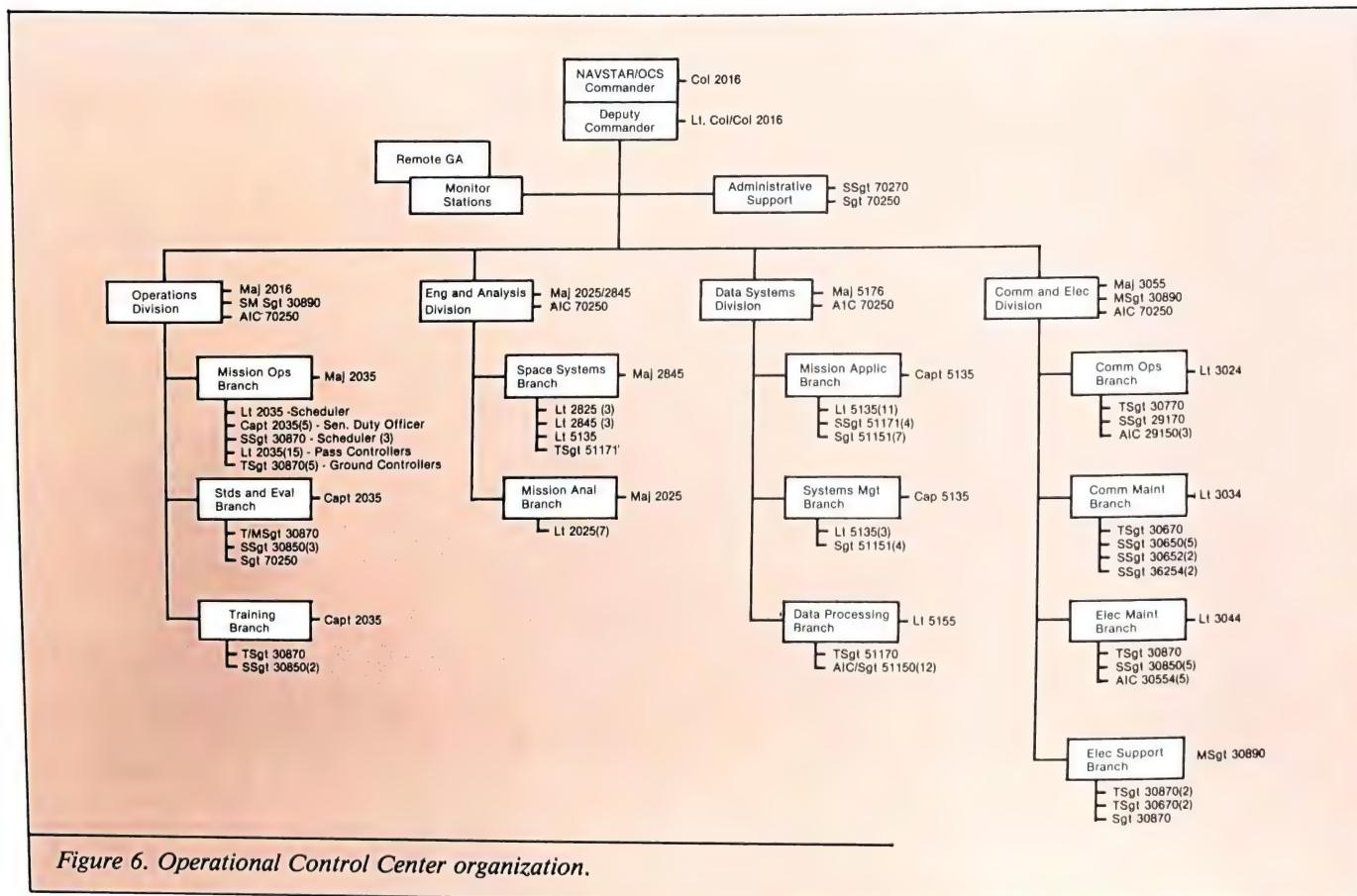
The Monitor Station computer will be an IBM Series 1 with a remote Initial Program Load (IPL) capability from the Master Control Station. The computer will direct initialization, run diagnostics, operate the interface with the Master Control Station using SDLC, implement the receiver tracking schedule, collect receiver channel data, collect local environment data of temperature and humidity, collect local status data, control the frequency standards and collect measurements of the phase differences between the two frequency standards.

The receivers will use dedicated channels for tracking of an SV. Each channel has two demodulators for measuring ADR and PR at both L1 and L2 frequencies. This provides 100 percent signal monitoring and maximum measurements. Only one P-code

Activity	Time (Minutes)					Inter Act	Frequency Per 24SV Constel.	Remarks
	SDO*	PC*	NS*	SE*	GC*			
Navigation Upload		16	2				3/hr	
Earth Eclipse Monitor	59 103 18					4/day	1 contact per orbit 28-48 day season 2 seasons/yr	
Moon Turn Monitor	70 19		61			2	4/day	6-10 day season 2 seasons/yr
Lunar Eclipse Monitor	39						4/day	Up to 2/SV
Address Key Upload	13	1				2	24/wk	1 upload/SV/week
Memory Dump	34	2				4	As req.	Anomaly Analysis
Gyro Recycle (during upload)	16	2					24/mo	
Z-count Adj.	21	6				4	As req.	1 Every 2 years (approx)
C-field Adj.	1	16	6			4	As req.	Initialize new clock
Station Keeping	51		31			2	1/yr	
Rephasing	51		31			2	1/yr	
Sta. Acquis.	51		31			2	1/yr	
Batt. Recond. (during upload)	16						24/sets/season	Prior to Earth eclipse season
Minor Anomaly	2	20	2			2	2/wk	
Major Anomaly	79	161	2	158		5	1/mo	

*SDO - Senior Duty Officer
PC - Pass Controller
NS - Navigation Specialist
SE - Space (Vehicle) Engineer
GC - Ground Controller

Figure 5. Satellite Vehicle activity summary.



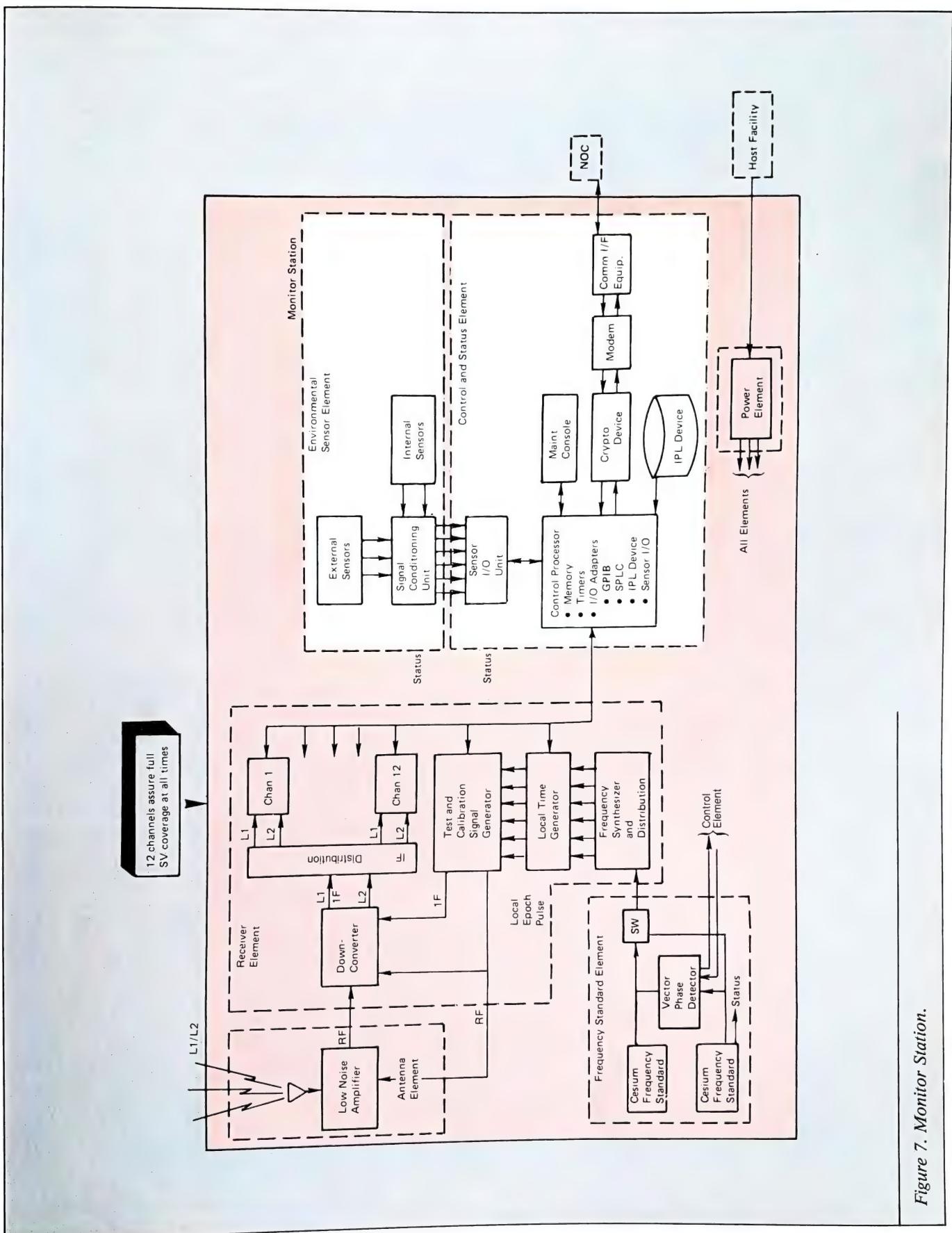


Figure 7. Monitor Station.

lower risk than a distributed processor approach.

A Master Control Station Computer sizing study was performed to estimate the size of the processor and its utilization given a functional design and operational workload. The sizing study led to the selection of the IBM 3033N8 based on the Performance Results shown on Table 6. The estimated load was 42.38 percent for the 24 SV constellation, and four simultaneous streams of 8000 bits per second telemetry. The processor was required to provide 50 percent spare capacity for expansion. Representative software run to benchmark the processor provided a lower utilization, 32.62 percent, as shown.

During the development of the Operations Concept the interface between the operators and the OCS hardware/software was analyzed. Particular attention was given to those human factors aspects which would simplify the man-machine interface. Different types of displays, information content, command actions, and alarm presentations were studied to determine the design of the mission operations consoles.

In the resultant design each console consists of two color graphic CRTs, a light pen, alpha-numeric keyboard and program function keys. One of the CRTs is interactive, providing a means for schedule dispatching, SV commanding, OCS reconfiguration, display selection and system alarm indications and acknowledgment. The second CRT provides for the display of detailed and summary status information. Primary operator input is through the use of the light pen and menus for dispatching the schedule, selecting displays, executing commands and acknowledging alarms. An operations language, based upon mnemonics with defined sets of arguments, provides for simple consistent input as well as system flexibility. Ten specially designed mission consoles are provided. Mission operations stations have an optional hard copy unit, which provides the operator with a record of events shown on the CRT.

The station's two-processor architecture requires that a reliable element also be able to detect a primary failure. The mission operations consoles each have access to both processors. Each console is able to detect within two to three seconds that the primary is not in control. An alarm is issued at each console

Table 5. MCS Load Requirements

Requirements	Notes
Generate 4 navigation uploads per SV per day	Average is 4 per hour for 24 SVs
Generate 3 backup navigation uploads per SV per day	Average is 2 per hour for 24 SVs
Process 4-8K bit telemetry streams simultaneously	This requirement represents a peak condition
Receive SV tracking data continuously from 6 MSs at the rate of 4 measurement sets per second	This data will be blocked to provide efficient use of the communication circuits and the communication interfaces
Perform an estimate of SV orbit and clock state as Epoch every 15 minutes for 24 SVs	
Service 4 command contacts per operational SV per day	Can be combined with navigation upload messages
Receive and process station status data at one minute intervals from all stations	
Support one anomalous SV per day	Telemetry included within the 4 continuous streams
Perform trajectory generation computations on 32 SVs for preference ephemeris	Trajectory computations on operational SVs (24) performed at 2 week intervals - non time critical
Two attitude determination sessions per day	No additional telemetry
One attitude maneuver session per day	No additional telemetry
Determination parameters for one thruster firing per day	No addition telemetry

at which time the Ground Controller can initiate the recovery. This can be expanded to automatic switchover in the future. An important aspect of this approach is that the consoles remain operational and in control during the recovery process.

To avoid frequent interrupt processing due to data needs of the GA and Monitor Station, a communications controller was designed into the configuration for responding to the servicing needs of communication lines. It performs the line control, polling, addressing, error recovery and buffering of data for efficient transfer to and from the main host processor. The controller selected is the IBM 3075 Communications Processor.

As in the case of the main processor, two communication controllers are needed to provide the necessary redundancy. To provide flexibility in switch-

over, each communication controller has separate and distinct connections to each processor. Each controller can handle the entire communication load.

Direct access storage devices and tapes are also accessible by both processors so that programs, current data bases, and data logs are available in event of switchover. Those data sets whose loss would be catastrophic to operations are maintained in two copies through two independent data paths to two independent physical disks. Each program must leave the data base in a determinable position for recovery. When a disk or data path fails, operation continues with the second copy until restoration is complete. The configuration includes three IBM 3340s and three IBM 3350 Direct Access Storage Devices on each processor for a total of six. This provides 4.6 Gigabytes and slightly exceeds the requirement of 100

Table 6. CPU Load

ESTIMATED LOAD—3033N8

Functional Unit	Utilization Percent	Functional Unit	Utilization Percent
Telemetry	12.33	GA Communications	1.29
Ephem/Clock—prediction	7.42	System Performance Evaluation	1.21
Misc.	5.61	Ground Status	0.20
Ephem/Clock—estimation	4.79	MS Control	0.12
MS Data Capture	3.01	Transmission Control	0.09
MS Communications	2.51	Command Message Generation	0.05
MS Data Processing	1.93	Upload Message Generation	0.02
Control/Display	1.77	Tracking Message Generation	0.00
		TOTAL	42.38 percent

BENCHMARK RESULTS—3033N8
PROCESSOR UTILIZATION (%)

	Overall System	MVS	CCS Services	CCS Telemetry	Ephemeris Clock Svc.	Navigation Upload
1.5 Average Peak Load	35.18	13.65	3.54	4.73	5.08	8.18
Average Peak Load	32.62	11.96	2.89	4.51	5.08	8.18
.5 Average Peak Load	28.98	9.56	1.84	4.32	5.08	8.18

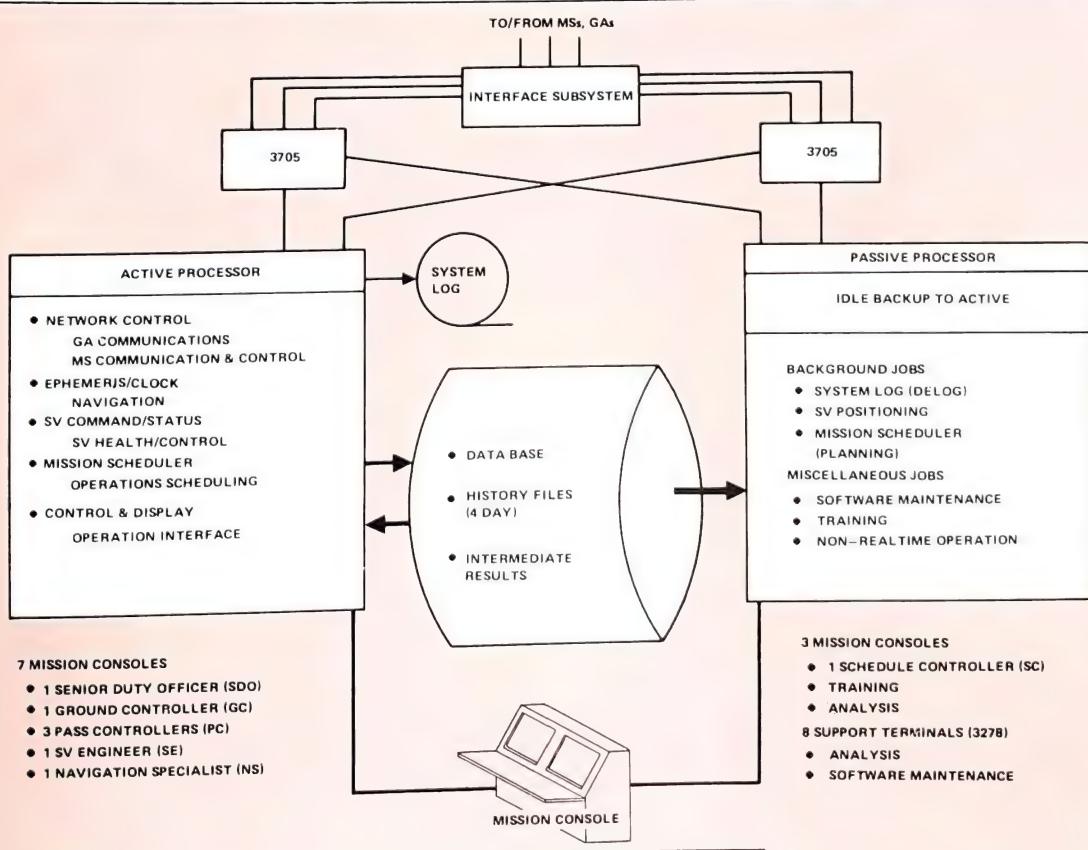


Figure 9. Master Control Station.

Table 7. Computer Program Functions

SYSTEM/370 SOFTWARE

Ephemeris and Clock

- Data Editing
- Clock State Estimates and Estimate of Quality
- Ephemeris State Estimate and Estimate of Quality
- Ephemeris and Clock Predictions
- Generation of Upload Parameters
- System Time Monitoring
- MS Receiver Calibration
- Controller Alerting
- Ephemeris and Clock Prediction Performance Monitoring

Network Control

- Network Configuration
- Control of GA Operations
- Control of MS Operations Including Receiver Scheduling
- OCS Subsystem Status Evaluation
- Readiness Tests of GAs and MSs

Mission Scheduler

- Provides Immediate and Long Term Support Schedules Based on SV and OCS Needs

System Log

- Record Inputs, Outputs and Mission Operation Events
- Condense, Merge, Compare and Create New Log Files
- Reconstructs Events and Sequences

SV Command and Status

- Telemetry Processing and Calibration
- SV Controller Alerting
- Command Generation
- GA Antenna Tracking Messages
- GA Pass Directory
- Navigation Upload Formatting
- Command Validation and Authentication

Control and Display

- Controls Console Configuration
- Supports MCS Recovery
- Provides Graphic and Alphanumeric Displays
- Processes Console Directives
- Alarm Interpretation and Presentation
- Controls Display Formats

SV Positioning

- SV Station Keeping and Attitude Control
- Visibility Profiles
- SV Momentum dump Computations
- Eclipse Data
- Solar Array Positioning Data
- End-around Checks for Ephemeris and Clock

Scenario Generator

- Generates Telemetry and Navigation Data for Testing and Training

SERIES/1 SOFTWARE

GA Program

- Station Configuration and Initialization
- Readiness and Diagnostic Testing
- GA/MCS Communication
- Antenna Pointing Angle Computations and Antenna Control
- Telemetry Storage and Playback

MS Program

- MS Configuration and Initialization
- Readiness and Diagnostic Testing
- MS/MCS Communication
- Control of Receiver Assignments
- Environmental Sensor Control
- Frequency Standard Control

MS Receiver Microcode

- Receiver Assignment Modes
- Code Loop Control
- Automatic Frequency Loop Control
- Phase Lock Loop Control
- Gain Control
- PR and ADR Measurements
- NAV Message Detection and Parity Checking
- Receiving Diagnostics

percent reserve over the need for 2.26 Gigabytes. IBM 3420 Tape Units and high speed printers are supplied for each processor.

Computer Programs

The functions of the Computer Programs used in the Monitor and Master Control Stations and Ground Antenna are listed in Table 7. Estimates of the source lines of code in the mission programs are approximately 350,000. In addition, IBM will provide more than 250,000 off-the-shelf lines of code exclusive of the operating system. Software design and operations will use the full capabilities of OS/VS2 Multiple Virtual Storage. MVS provides job and task management, input/output access methods, memory management, and disk support. Its capabilities include maintenance aids and recovery management facilities to support fault detection, isolation and repair of the MCS without mission support processing termination.

To reduce system development risk the Command and Control System, Control portion (CCS/C) developed by IBM to support the NASA Shuttle program is used as the real time executive. The real time executive controls the processing of events which occur at random times, some dependent on external events, some at scheduled events and others dependent on controller actions.

The Ground Antenna and Monitor Station both use the same real time executive program which provides for the initial program load, supervisor services, data management, communications with the Master Control Station, utilities, and debugging aids.

Software Design Control Requirement

The Navigation String (Figure 10) provides one example of how the GPS controllers interface with the software through the mission consoles and the active processor. To support a navigation upload, the Ground Controller oversees the OCS performance and will monitor the Monitor Station and GA status in collecting station measurements and telemetry prior to upload. Evaluating the performance of the Ephemeris and Clock Prediction program by reviewing intermediate calcu-

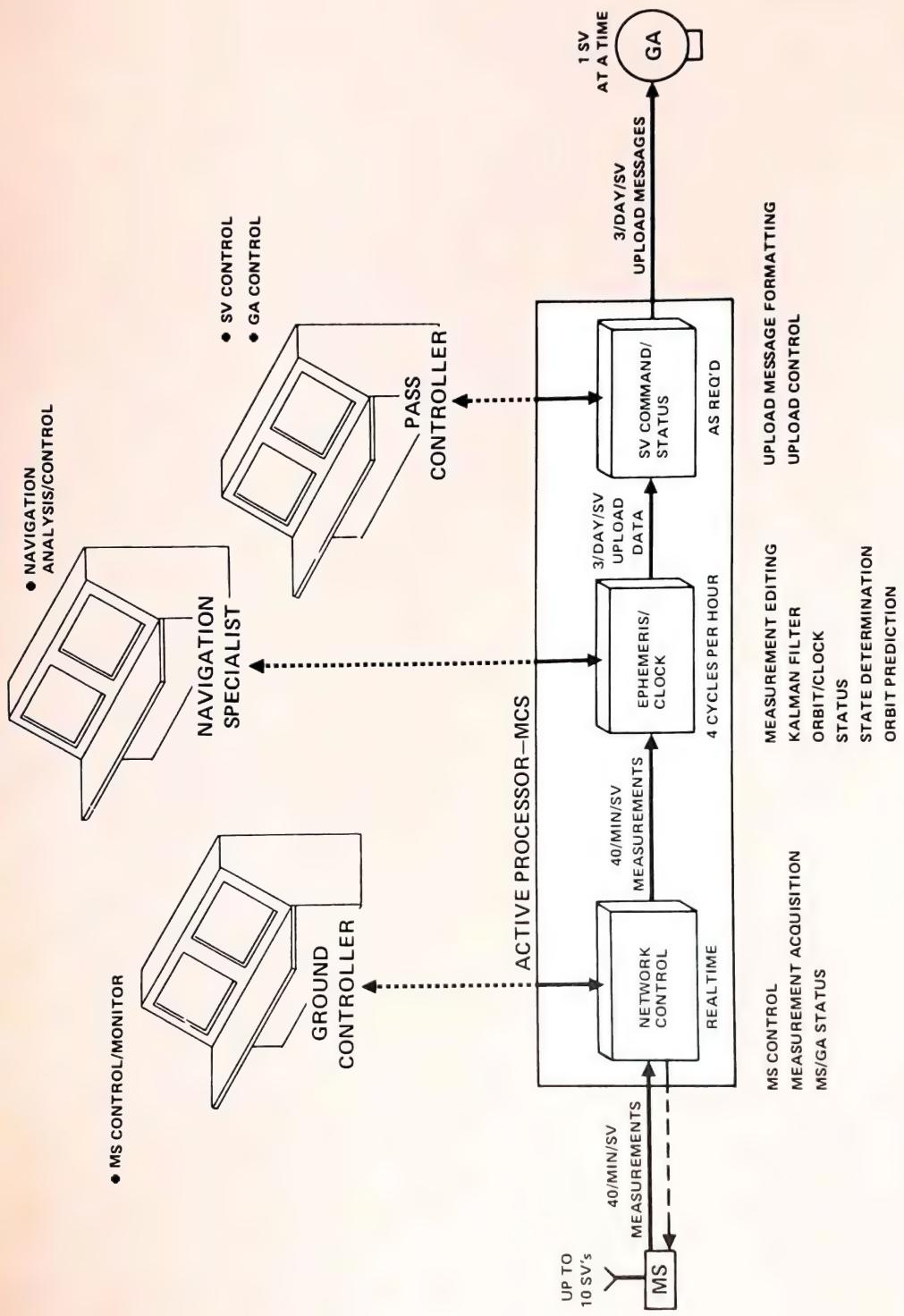


Figure 10. Navigation String.

lations in the state estimation process is the Navigation Specialist. The Pass Controller will review the status of the SV prior to upload and oversee the operation of GA during the upload.

The software provides the means for Pass Controllers to assess SV uploads through real time verification and to provide Navigation Specialists with straightforward approaches to modifying ephemeris and clock correction prediction parameters if navigation solutions deviate from known solutions. As mentioned above, the OCS software represents the single most significant challenge to the successful development of the GPS system into a reliable military support system, easily operated by military personnel. Consistent, reliable software is a must. The GPS software development process is taking advantage of those software engineering practices which have evolved in the Federal Systems Division. These include:

1. Software design practices which provide a complete and coherent methodology for system definition, module design and program documentation.
2. Software development practices which provide languages, conventions and standards, and software development tools to manage the software as design specifications are reduced to code and the code is integrated into a system product.
3. Software management practices which provide the plans and controls for determining that the technical schedule and cost performance goals for the product are being met from design through development.

The software development process makes use of one of the IBM 3033N8s to be installed at the Master Control Station and an IBM Series 1 in a Software Development Laboratory (SDL) at IBM in Gaithersburg, Maryland. Telephone

links will be provided to accommodate software development at the Initial Control System at Vandenberg and to subcontractor locations involved with developing software for ICS and OCS. Support software running under OS/MVS Time Sharing Option at the SDL includes the following software tools:

- structured programming facility
- program management facility
- program design language
- language processors
- library maintenance
- configuration management and reporting
- system build software
- SCRIPT

Summary

The GPS System is planned to meet the DoD's need for precise navigation into the 21st century. The OCS is designed to support the full space constellation of 24 SVs and eight spare SVs as well as grow to meet expanding requirements. A secondary payload, the Integrated Operational Nuclear Detection System, will be on the GPS spacecraft. Ground control of that payload as well as other payloads which may be added later can be accommodated by the expansion capabilities of Operational Control System.

Life cycle costs, particularly as they are effected by the number of people needed to operate and maintain the control system, were central to the design process and will continue to be of prime interest as the system develops and becomes operational. The software should provide further opportunity to reduce operator interaction and further minimize life cycle costs.

In the years ahead, GPS will revolutionize military operations and promises even greater benefits to civil needs.

Acknowledgements

The OCS design effort reported on in this paper draws upon the contributions of many people during the Stage I Study and Proposal and the subsequent efforts since the award of the OCS development contract. These included W.D. Carson for system engineering; S.G. Francisco for overall technical leadership as well as systems analysis in receiver design, ephemeris prediction process and the clock predictor; R.D. Dancy system architecture and design; R.W. Gretz, Master Control Station architecture; R.C. Crutchfield, receiver design and ephemeris and clock software; J.E. Henrich, accuracy analysis; E.A. Keese, remote site location analysis and activity timeliness; D.R. Hope, operations analysis and concept. The author expresses appreciation to S.G. Francisco, J.F. Durkin, D.M. Welsh, and A.B. Adkins who contributed many ideas and suggestions during the development of this paper.

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DSM: New Generation Of Satellite Control

by Kenneth J. Deahl and Thomas C. Wellington

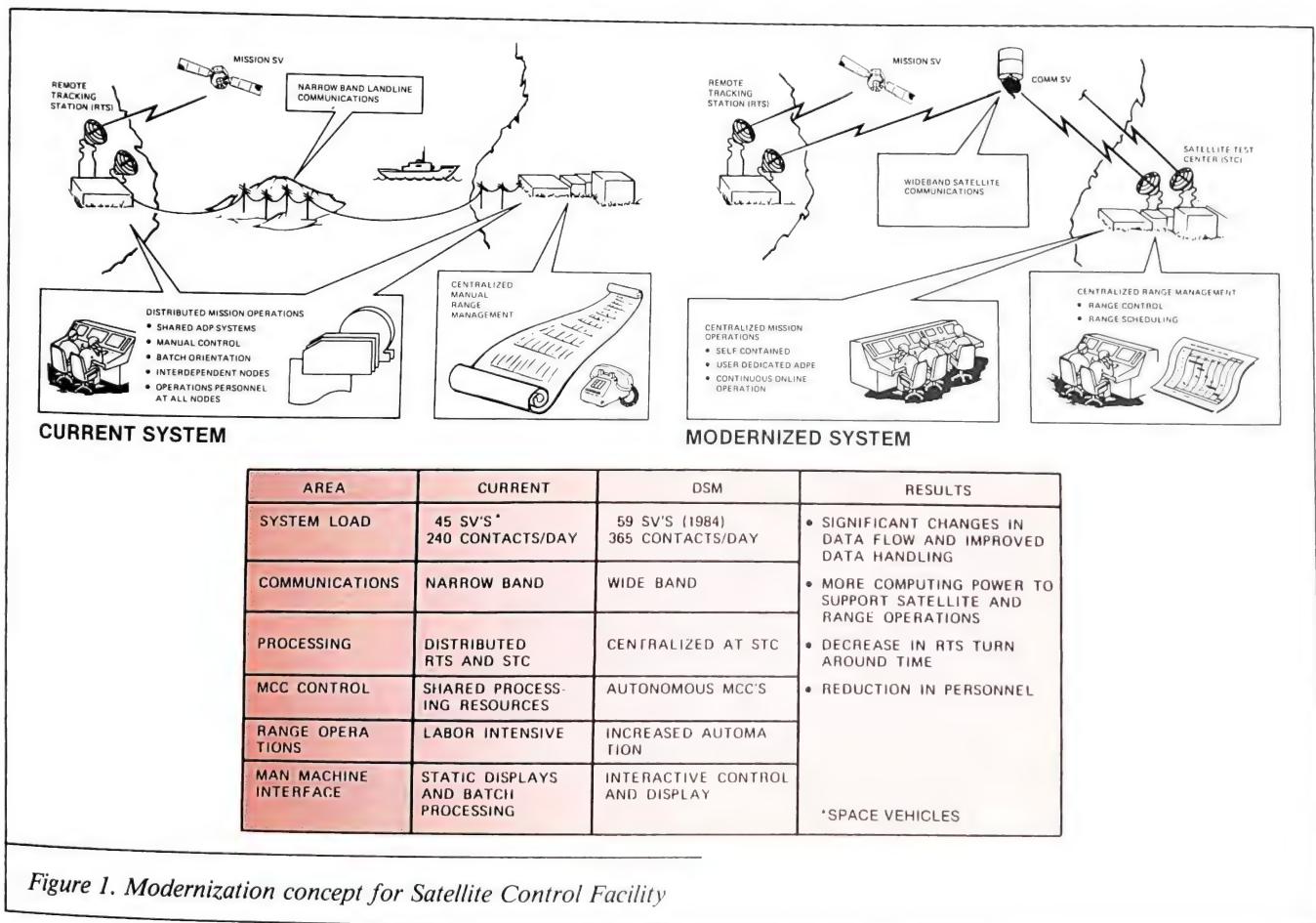
The Air Force, through an industry team headed by the IBM Federal Systems Division, is advancing the Command and Control Segment of its worldwide Satellite Control Facility (SCF) from second to fourth generation computer hardware and is modernizing the system architecture. Under a six-year prime contract which was awarded to IBM in December 1980, IBM is upgrading the SCF network data system to handle the increased volume of space traffic expected into the next century.

The enhancement, known as Data System Modernization (DSM), also will improve operations and significantly reduce operating costs by transferring more of the data processing work from the Remote Tracking Stations to the Satellite Test Center located at Sunnyvale, California.

The present SCF network, built around computer hardware based on small-scale integration (SSI) components from a variety of suppliers, is barely keeping up with the workload. Current capacity is estimated at about

100,000 contact supports per year; together with other SCF upgrades, DSM will increase that to more than 200,000 per year. (A contact support is the activity in a continuous interval of communication between a satellite and a Remote Tracking Station.) Figure 1 shows the basic differences between the current system and the modernized system.

Using commercially available IBM mainframes and small computers with large-scale integration (LSI) components, combined with off-the-shelf



technology, specialized interface hardware and software derived in part from current programs, DSM will transform the SCF's operations from batch-oriented shared to centralized, interactive operations. Despite a projected doubling of satellite contacts, DSM could reduce manning requirements — an important saving.

This capability to handle an increased load is based on a design similar to that created by IBM for the Shuttle Ground Based System. It includes the functions of realtime, interactive control of space vehicles and ground resources from autonomous control centers; realtime processing of telemetry, tracking and status data; computer-interactive planning and evaluation functions (including, for DSM, full graphics displays for telemetry analysis); centralized control of range resources; and an incremental approach to range scheduling automation.

Among the driving factors in the DSM design (Figure 2), reliability is

the principal one and requires 0.999 probability of completing a 30-minute spacecraft contact. Also, although the 1984 system implementation requirement is for about 30 Mb/S of telemetry data, DSM must be designed so that it can be upgraded to 525 Mb/S. Technical risk and transition problems are to be minimized.

Part of the overall Satellite Control Facility improvement program is a shift in communications mode from narrowband-landline links to wideband satellite communications (the "bent pipe"). Under DSM, the 12 antennas at seven Remote Tracking Stations at Vandenberg AFB; Thule, Greenland; United Kingdom; Guam; Hawaii; New Hampshire; and in the Indian Ocean will feed their data directly to the Satellite Test Center, which houses all the computers for dedicated Mission Control Complexes, the Range Control Complex and the System Development and Test Laboratory. The global operations of the SCF, including a Remote Vehicle

Checkout Facility at Cape Kennedy, are shown in Figure 3.

Each of the Mission Control Complexes operates autonomously for a designated Air Force Vehicle Office.

The Range Control Complex has the demanding task of overseeing all SCF resources (a task now performed manually, for the most part) to match the antenna and satellite schedules—a task that is expected to become even more demanding as the number of satellites in orbit grows and includes more complex vehicles such as the Air Force Space Shuttle. The System Development and Test Laboratory is a replica of a Mission Control Complex for developing and testing new control procedures and software.

Five Segments in SCF

To understand the significance of the Data System Modernization program, it is necessary to understand how the entire SCF works. There are five segments in the SCF, and DSM is the program to upgrade one of them,

DRIVER	REQUIREMENT/OBJECTIVE	ARCHITECTURAL IMPLICATION
TELEMETRY LOAD	DESIGNATED COMMUNICATION RATE: 525 MB/S IMPLEMENTED COMMUNICATION RATE (1984): 30 MB/S	ARCHITECT FOR GROWTH DESIGN TO EXPECTATION
TRANSITION	RISK FREE	MODULARITY/SYMMETRY MINIMAL DISPLACEMENT DEDICATED RESOURCES
RELIABILITY / AVAILABILITY	UP TO 0.999 NO SINGLE POINT SYSTEM FAILURE	REDUNDANCY RAPID SWITCHOVER OR DISTRIBUTION
GROWTH	HORIZONTAL, VERTICAL	POOL HORIZONTAL GROWTH RESOURCES MODULARITY
RISK	MINIMIZE	SIMPLICITY RESOURCE DEDICATION

Figure 2. Driving factors for DSM system design

the Command and Control Segment. This segment contains the data processing, display, control, distribution and interface hardware and software necessary for Mission Control Complex operations, range planning and scheduling, range resource configuration control and the overall management of the SCF. The other segments are:

Telemetry, Tracking and Commanding Segment located at the Remote Tracking Stations and the Remote Vehicle Checkout Facility. This segment is composed of antennas, receivers, transmitters and signal conditioning equipment. The Telemetry, Tracking and Commanding Segment performs pre-launch satellite checkout, acquisition and tracking of satellites, reception of telemetry and ranging data, transmission of commands to the satellite, and transmission to the Satellite Test Center of received telemetry and ranging data via the

Communications Segment. Tracking and status data are routed to the Satellite Test Center via the DSM Remote Tracking Station/Remote Vehicle Checkout Facility Control and Status Equipment (RCSE) associated with each antenna. The RCSEs are part of the Command and Control Segment and are included in the modernization program.

Communications Segment, which has as its major function communication among all other segments of the SCF system, NASA and other external users. The Communications Segment also performs communication security and data recording functions for the SCF. This segment provides the control and interface equipment associated with the communications satellites, landlines and microwave circuits for transmission of data, voice, teletypewriter and facsimile information. The baseline

"bent pipe" communications network consists of DSCS II relay satellites. A 9600 b/s landline is the backup for the Communications Segment.

Support Segment, which includes the SCF timing equipment at each Remote Tracking Station and the Satellite Test Center, and the Camp Parks Communications Annex equipment that supports on-orbit satellite performance tests. The Command and Control Segment depends on this timing support for the functions of command transmission, command verification, telemetry recording and processing, tracking/ephemeris processing, configuration and status monitoring, simulation, data recording/archiving, display, vehicle clock calibration and hardware maintenance/fault isolation.

Facilities Segment, which provides the physical, electrical and environ-

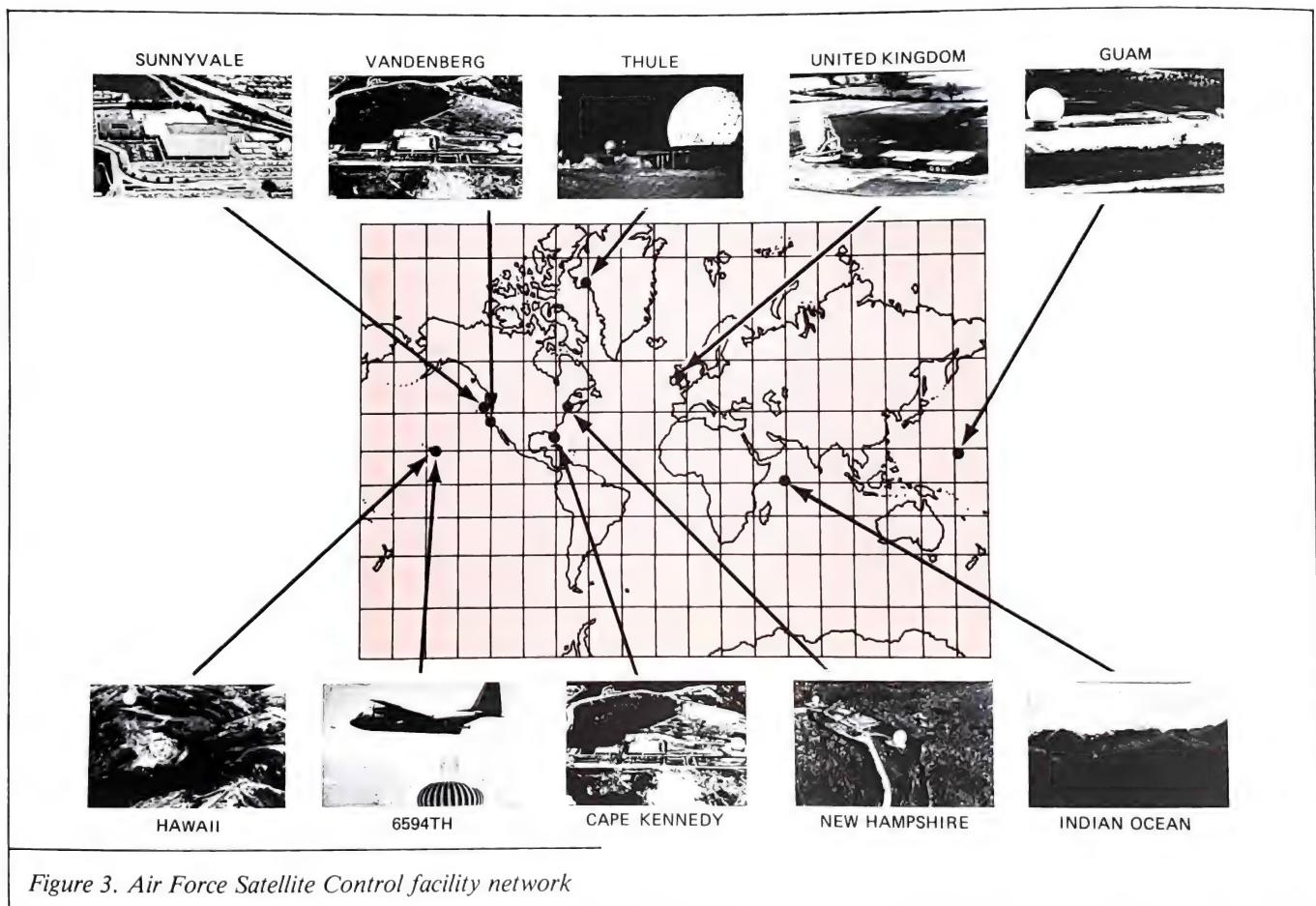


Figure 3. Air Force Satellite Control facility network

mental elements that are required at the Remote Tracking Stations, the Remote Vehicle Checkout Facility, the Camp Parks Communications Annex, and the Satellite Test Center.

DSM enables the Command and Control segment to be integrated with all the other segments of the SCF into a smoothly functioning system with greater throughput and reliability. Figure 4 shows an extension of the SCF to include a Satellite Operations Center at Colorado Springs, Colorado, which could be provided under a contract option to serve as an alternate Satellite Test Center.

The DSM Team

IBM's Federal Systems Division, which has total system performance responsibility for DSM, heads a team of subcontractors and other IBM divisions. The program is managed from the IBM facility at Gaithersburg, Maryland, using many IBMers drawn from previous IBM space-related efforts such as Apollo, Skylab, and Space Shuttle. An additional IBM office has been established and staffed at Sunnyvale for on-site support.

Three other IBM divisions are participating in the program. The Data Processing Division (DPD) is supplying all the computer mainframes—three 3033 large-scale systems capable of operating at five million instructions per second (MIPS) and seventeen 4341 medium-scale systems operating at around 1 MIPS. The General Systems Division is supplying and maintaining 70 IBM Series/1 computers to serve as front-end processors. The Field Engineering Division is supporting the program with installation and on-site maintenance of DPD-supplied commercial hardware and software.

The principal hardware subcontractor on the DSM team is Harris Corporation, which is developing the remote site RCSE subsystem for the Remote Tracking Stations and the Data Distribution Subsystem at the Satellite Test Center. Harris is responsible for the special interface equipment that will handle the increased data rates required in the enhanced DSM mode.

Also supplying hardware is Sanders Associates, a manufacturer of high-

resolution (1000 lines) color and monochromatic video display terminals to be used in the DSM consoles. The company is providing 42 dual screen terminals (graphics with color and monochrome).

There are six software and engineering analysis subcontractors on the DSM team; four of them are designated small business concerns by the Small Business Administration. These six companies are:

Litton Mellonics Division, developing the commanding programs and the interface software to enable DSM to interface during the transition stage with present equipment that is to be retired.

Infotec Development, Incorporated (small business), handling the operational concept planning, display format design, man-machine interface, personnel requirements and DSM position handbooks.

RDP, Incorporated (small business), providing the support software for maintenance and logistics.

Computer Technology Associates, Incorporated (small business), supporting the development of the tracking and orbit determination specifications and algorithms.

Systems and Applied Sciences

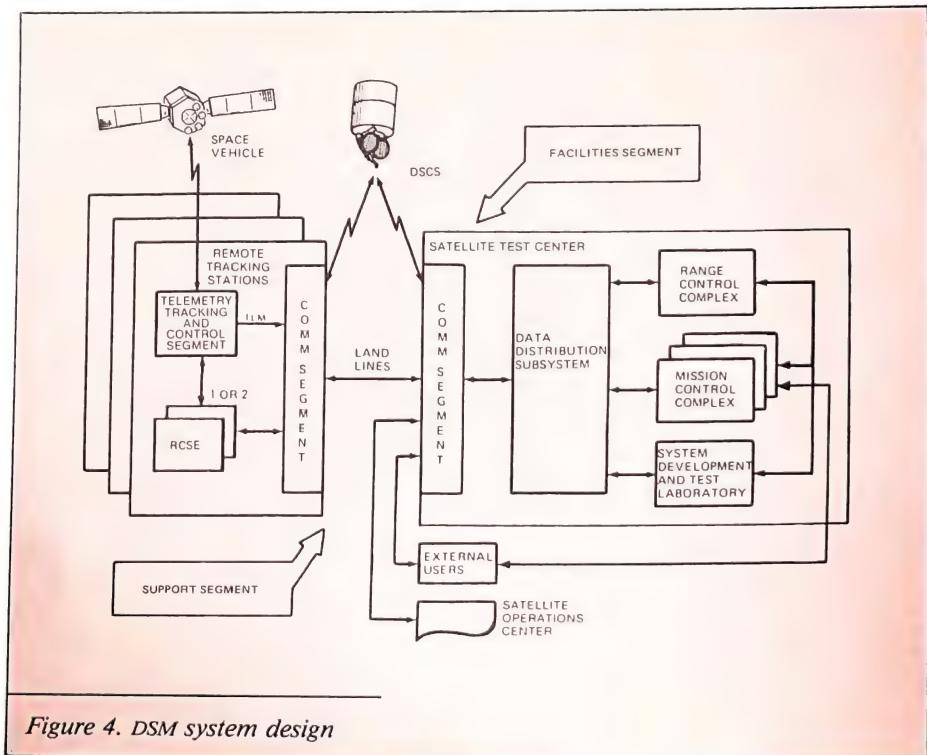
Corporation (small business), developing tracking and orbit determination software.

SCITOR Corporation, (small business), performing systems engineering for the test and integration activities.

Completing the IBM subcontractor team is Lockheed Missiles and Space Company (LMSC), which has provided operations, engineering services and modifications support to the Air Force at the Satellite Test Center for 20 years. As a participant in DSM, Lockheed has major responsibilities for planning the facility, preparing the site, installing the system, training operations personnel, supporting the integrated logistics support management system, developing operational consoles and assisting the test and evaluation efforts.

Hardware Commonality

DSM introduces 10 new computer systems into the SCF. These are commercially available, state-of-the-art systems, each consisting of dual mainframes with shared peripherals and seven small computers. To avoid designing 10 separate computer complexes for 10 separate user groups—thus requiring ten complete system development and integration jobs—a



"system kernel" architecture approach has been used.

A system kernel is the basic configuration that is duplicated for each of the Mission Control Complexes, the Range Control Complex and the System Development and Test Laboratory. All use dual IBM 4341 processors except for the System Development and Test Laboratory and one Mission Control Complex which requires the greater power of 3033s. Also, all of the kernels use the same standard IBM OS/MVS operating system.

The system kernel architecture is a symmetrical configuration (Figure 5) that concurrently supports both the high priority task of realtime spacecraft contact support and lower priority planning and evaluation. The planning and evaluation processor can be switched to the higher priority task within 85 seconds, thus achieving a 0.9994 contact support mission reliability. The kernel CPUs share dual IBM Series/1 computers, which serve as front-end processors, a shared disk system averaging 5.5 gigabytes of storage per Mission Control Complex, five additional IBM Series/1 computers linking the system to the SCF network, and other periph-

erals as needed, such as printers, tape units and displays. All equipment in Figure 5 is supplied by IBM commercial divisions except for the Sanders displays and the Harris Command Contact Support Equipment Group (CSEG) units which are part of the Data Distribution Subsystem.

Hardware development is minimized through reliance on standard commercial data processing equipment, which offers the additional benefit of having sufficient compatible growth capability for future upgrades. An estimated 95 percent of all DSM hardware is off-the-shelf—70 percent through IBM commercial divisions and the other 25 percent, such as the displays and much of the Harris equipment, from other commercial suppliers.

The remaining 5 percent, principally the RCSE units from Harris, represents minimal technical risk. No new technology is involved, and there is no need for special integrated circuits or custom processors.

Software for Growth

The DSM architecture will use 27 Computer Program Configuration Items (CPCIs) plus mission unique Auxiliary Master Tape (AMT) CPCIs

for a total of 1.2 million source lines of code (SLOC) to be delivered. This is in addition to 33 IBM licensed program software products, which represent another 5 million SLOC. The DSM operating system will be the standard IBM OS/MVS equivalent to about 2.3 million SLOC, complemented by the IBM-developed Ground Based Shuttle Real Time Support System (RTSS) to optimize throughput and responsiveness. Both are also being used in the IBM development of the Navstar Global Positioning System Operational Control Segment.

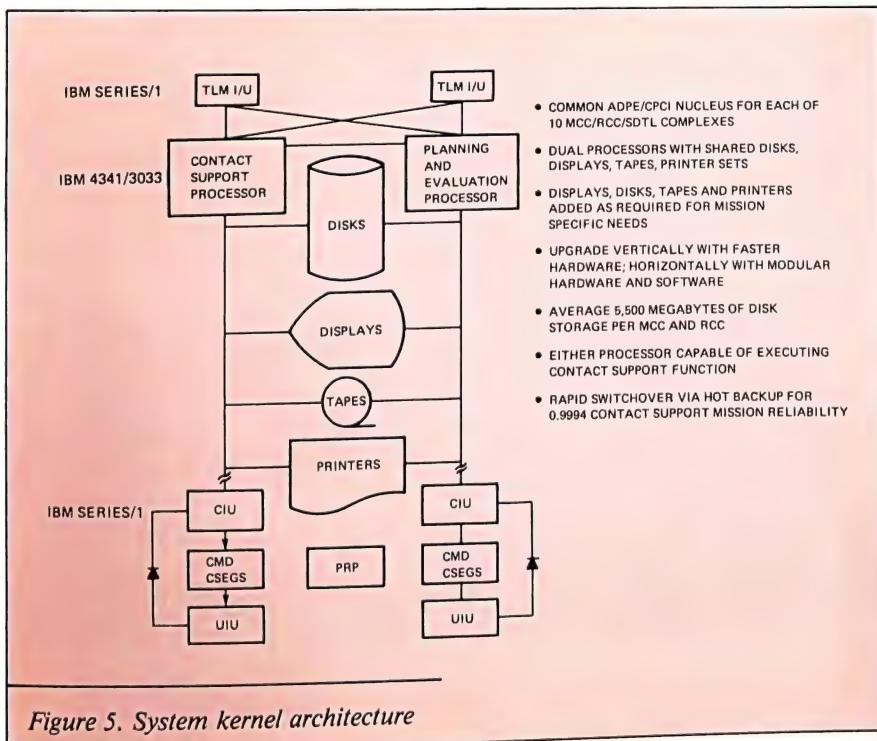
Of the 1.2 million SLOC required specifically for DSM, 250,000 SLOC are available directly from existing IBM Federal Systems Division products, and another 104,000 can be lifted and modified from these products. This leaves 845,000 SLOC, or 70 percent of the DSM requirement, to be developed as new code.

In the initial DSM design phase, IBM examined a number of high order languages, including Ada, Jovial (J73 version), Fortran and Cobol. The company chose Jovial J-73 as the primary language on the basis of its technical characteristics, availability in time to support the DSM mission, life cycle cost advantages, successful use for more than 10 years at the Satellite Test Center and its compatibility for future transition to Ada, which is still in development.

Jovial will be used for about 88 percent of the new code with the balance being Assembler (10 percent) and Extendable Computer Simulator (2 percent) languages. The software is being developed incrementally in three phases—an initial group of CPCIs to support an early program, a second group for all other vehicle operations and a third for the AMT conversion to product vehicle specific software for each Mission Control Complex. The software distribution by code type is shown in Figure 6.

Reducing Technical Risk

The IBM design for DSM takes maximum advantage of products and technologies proven in similar complex, realtime systems. Key features of this design that contribute to reduced life cycle costs and schedule risk minimization include the use of



IBM commercial products (hardware and software), existing products from the Shuttle Ground Based System, Jovial J73 and modern software engineering technologies for software development, and a basic system kernel architecture that is identical for all Mission Control Complexes, the Range Control Complex and the System Development and Test Laboratory.

Confidence in system performance is based on an analysis of specific required tasks in the context of an operational concept. As part of the design phase (1979-80), IBM "flew" a simulated satellite constellation that corresponds to the specified 1984 satellite scenario. The system load was established by modeling the space vehicle orbital characteristics, tracking station performance and telemetry rates. The simulation considered Remote Tracking Station utilization and the scheduling and telemetry loads for the SCF and each Mission Control Complex.

In addition to performance estima-

tion, areas of technical, schedule and cost risk were identified and assessed at the beginning and the end of the design phase. The number of high risk items was reduced from 10 to zero during this phase and medium risk items, from 63 to 56.

To support the development phase, IBM has established a program team at the Gaithersburg facility. An IBM facility with on-site staff at Sunnyvale is in place to provide systems engineering support and to coordinate with Air Force working groups on interface control, operations, telemetry processing and integrated logistics support management. Also at Sunnyvale, a prototype Remote Tracking Station (without antennas) will be used for test and integration.

DSM Implementation

Implementation of DSM (Figure 7) is proceeding in three overlapping phases: hardware development (principally the RCSE and Data Distribution Subsystem), software development and system test, and site activa-

tion and transition from the present system to the DSM mode.

Hardware development begins with the flow of preproduction models of the Data Distribution Subsystem/RCSE at Harris to IBM's DSM System Development Laboratory at Gaithersburg, consisting of a 3033 and 4341. This will be followed by checkout of initial production hardware at the System Development Laboratory in 1983 and additional checks of the first four operational RCSEs in Sunnyvale before delivery to the Remote Tracking Stations. Subsequent operational RCSEs are to be shipped directly to operational sites so that each Remote Tracking Station has at least one RCSE prior to system Initial Operational Capability (IOC).

The software development phase, conducted principally at Gaithersburg with support from the software subcontractors, is characterized by use of FSD Software Development Standards for top-down, structured programming. Development and test of the CPCIs will be conducted in the

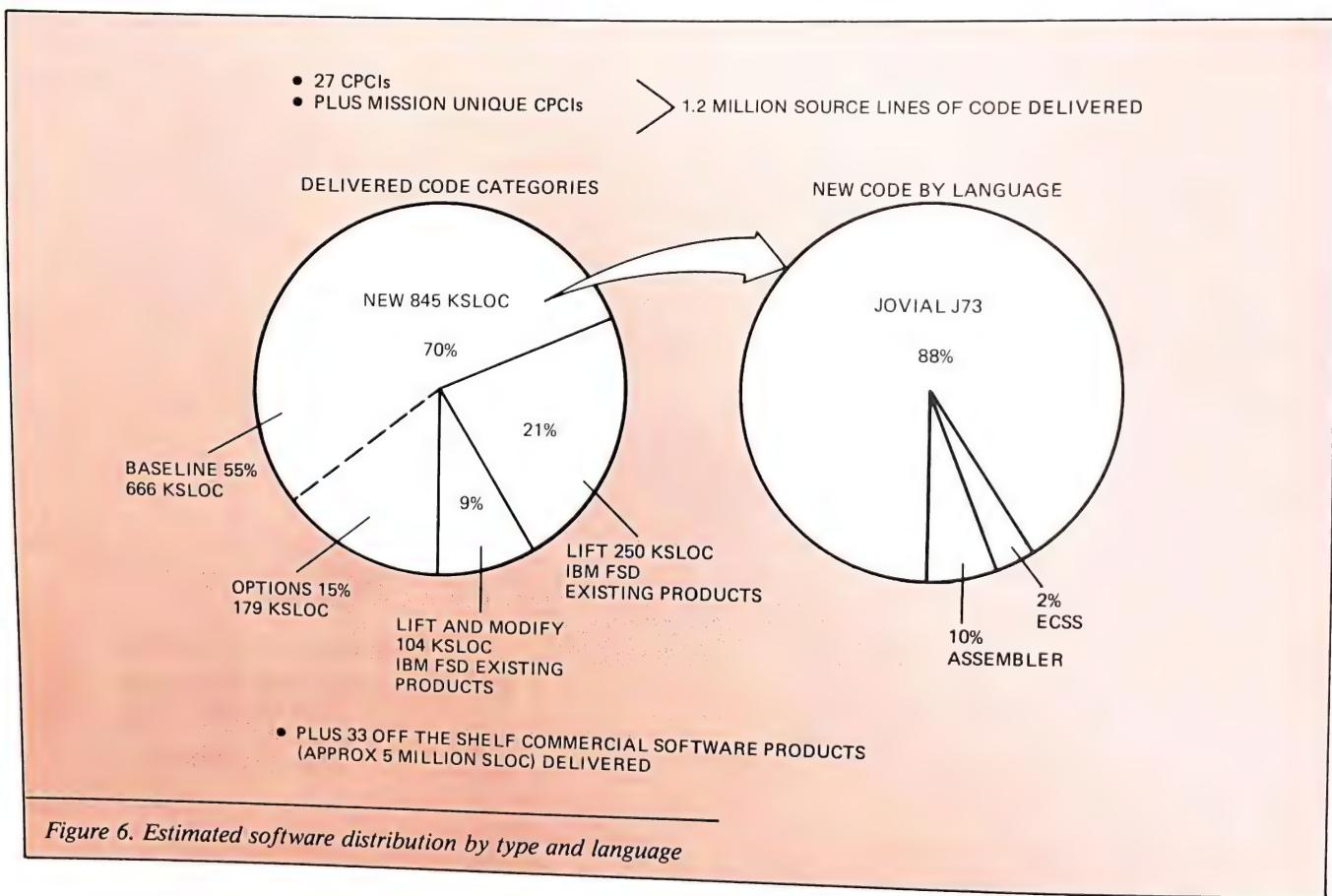


Figure 6. Estimated software distribution by type and language

System Development Laboratory, including those produced by Mellonics in Sunnyvale and transmitted to Gaithersburg. System test and integration are conducted in increments corresponding to the deliveries of hardware and software. Hardware development tests will be performed at Harris. Software tests, including Final Qualification Tests, will be performed in the System Development Laboratory by IBMers who will accompany the software package to the Satellite Test Center to assure a smooth transition to operational status for each Mission Control Complex.

The third implementation phase, site activation and transition, is complicated by the requirements that it be accomplished with minimum interference with on-going operations and without introducing any substantive risk to the space vehicles. Transition is done first at the Remote Tracking Stations as the RCSES are installed and put in operation. Since compatibility with the pre-DSM and DSM modes must be maintained through the en-

tire system transition period, a special hardware device known as the "Break-Out Unit" from Harris is essential. It is installed in-line between existing equipment to be retained and the new DSM hardware, and provides interface matching and rapid switching between modes.

Satellite Test Center activation will involve a substantial role by Lockheed in facility planning and training. IBM will manage implementation and transition from its Sunnyvale office. Survey plans, construction and site preparation are due to be complete for the first Mission Control Complex and the designated transition Mission Control Complex, MCC-T, in late 1983. The System Development and Test Laboratory should be ready for operation earlier that year.

MCC-T is the key to continuing SCF operations without interruption while DSM is being implemented. After being trained first in the System Development and Test Laboratory, Air Force and civilian Vehicle Office (VO) people for each Mission Control

Complex to be transitioned will begin operational exercises in MCC-T and proceed to qualification test and rehearsals. When the VO agrees that proficiency is at least equal to that achieved in the pre-DSM Mission Control Complex, the VO then certifies DSM operations on MCC-T. The transitioning Mission Control Complex is dismantled and outfitted with the new DSM equipment. The software is installed and reverified, and DSM operations begin in the pre-DSM MCC location. The next VO then starts its transition on MCC-T. In this way, any VO has the ability to restore its original operations during the transition phase if problems arise.

The total transition period for each VO involves about 16 weeks of training, eight weeks of parallel operations and 15 weeks of facility conversion (Figure 8).

Management

In order to satisfy the unusual demands created by this complex system development activity, the challenging implementation schedule and the geographic dispersion of development and installation sites, special attention has been given to the management tools and techniques.

As a cost and energy efficient method of coordinating the development work, video teleconferencing is being installed connecting the Sunnyvale and Gaithersburg offices, and is under consideration for other locations. This enables both large and small conferences to be conducted at substantial savings in both time and travel costs.

In schedule management, the use of E-Z-PERT*, which provides graphic outputs from tabular data bases, is providing flexibility of format and better visibility to critical paths in overall project schedules. In addition, near-term, detailed schedules are planned and reviewed in weekly meetings using computer prepared schedule charts.

DSM program management personnel have direct access to a comprehensive project data base through deskside display terminals, providing the capability to search through a subject index of correspondence and

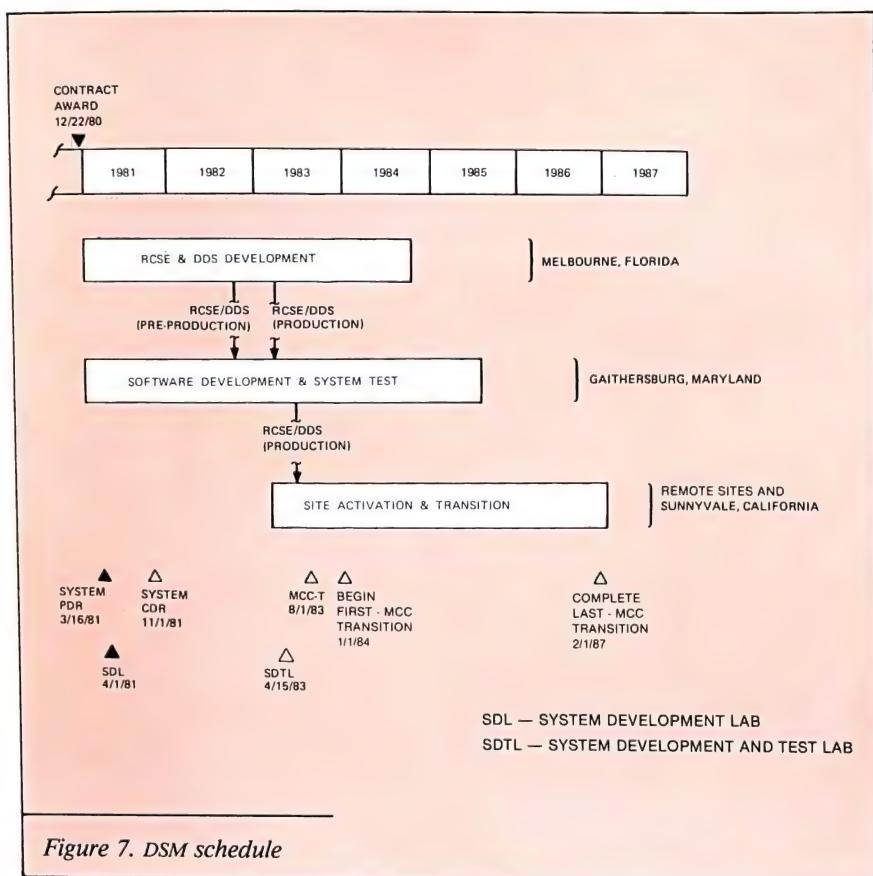


Figure 7. DSM schedule

* Registered Trademark, Systonetics, Inc.

project coordination notes. All specifications are being generated through a word processing system ("SCRIPT") based in the System Development Laboratory computers. Traceability between specification requirements and analysis of the requirements are assisted by the use of the Problem Statement Language and Problem Statement Analyzer (PSL/PSA).

Financial control is maintained in full compliance with DoD directive 7000.2, and uses IBM's automated system to provide weekly status and forecasts to cost account managers.

These modern aids and approaches are used to augment traditional program management techniques in the areas of subcontract management, logistics management, quality assurance, and configuration management. All system specifications and changes are under the control of the Configuration Control Board which

brings the system engineering and development managers together at least weekly to address current technical issues.

Summary

DSM will meet the Air Force's need for handling a growing volume of satellite contacts using fewer SCF operational personnel by employing state-of-the-art hardware and software. Life cycle costs are further reduced by using commercially available systems with greater reliability and therefore lower maintenance requirements. Mission controllers will receive their data faster and in a more legible format through the interactive capabilities of DSM.

Furthermore, the DSM architecture is inherently capable of growth to meet even more demanding requirements. Horizontal growth can be

achieved by adding more data streams and more Mission Control Complexes as necessary; vertical growth is ensured through large specified design margins and through the potential addition of higher capacity equipment, which would be compatible with the present hardware and software. DSM will bring major improvements to this vital defense program.

Acknowledgements

The system design of the SCF Command and Control Segment modernization was the product of many individuals working over a two-year period. Part of the design effort was supported by contracts with the Air Force Space Division. The authors wish to thank all of the project members for their contributions, and the Air Force for its support.

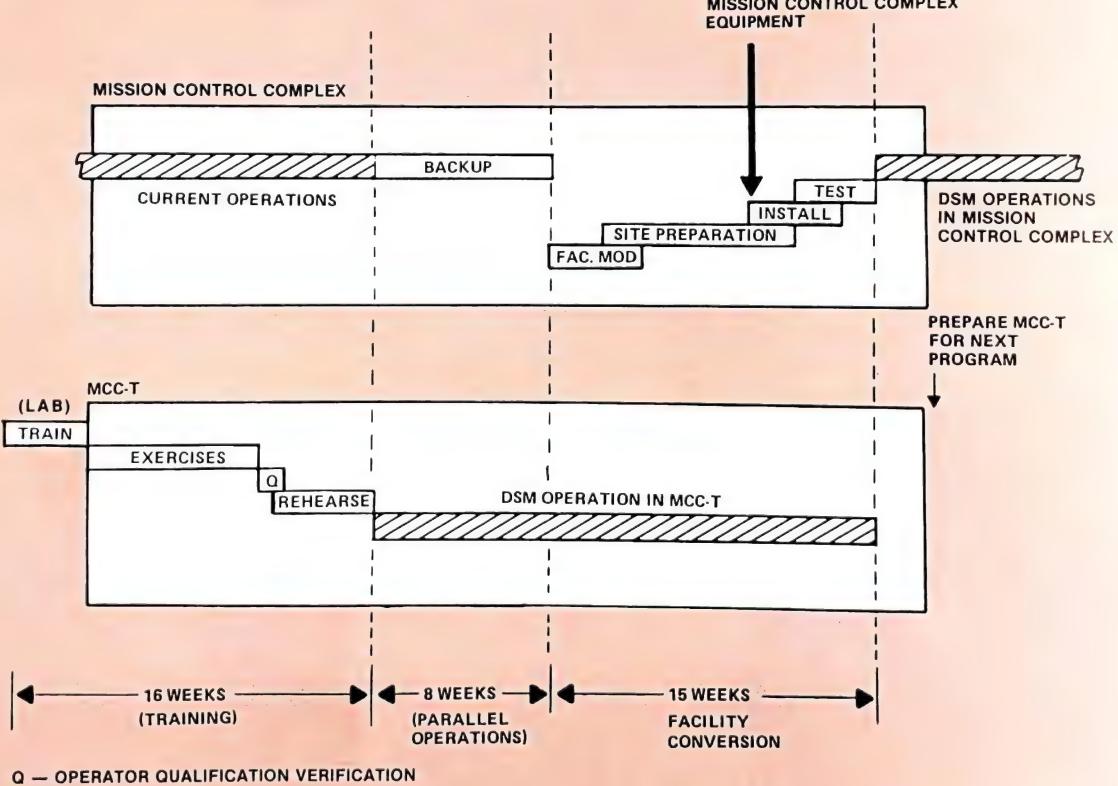


Figure 8. Transition of a Mission Control complex

Authors in This Issue



Commonality of Real-Time Command and Control

George A. Gaxiola joined IBM's Federal Systems Division in 1966. Since that time he has worked on a number of technical and management assignments in software development, specializing in real-time control programming for projects such as the Pioneer Plasma Probe, Mariner/Mars, CONUS Ground Station, Advanced Control System, Ground-Based Shuttle, and recently, Common Systems Development for the Data System Modernization and Global Positioning System projects. Currently, he is a senior programmer contributing to the DSM Program at IBM's location in Sunnyvale, California. Mr. Gaxiola holds a BS degree in Physics from the University of Mexico.



SOPC: DoD's Control Center for the Space Shuttle

Merritt E. Jones is a senior analyst in the Mission Analysis and Engineering group of the IBM Federal Systems Division in Houston, Texas. Since joining IBM in 1963, he has held several technical and management positions on manned space programs from Gemini through Space Shuttle. These assignments included development of large real-time systems in the onboard, ground and simulation areas. For the past two years, he has supported DoD in feasibility, concept and baseline studies for SOPC. His current assignments include supporting NASA and DoD in the planning and study efforts leading to an operational SOPC. He holds a BS in mathematics from Millsaps College with graduate work at the College of William and Mary.



Launch Processing System for STS and DoD Shuttle

Don G. Satterfield, Launch Processing System program manager at the IBM Cape Canaveral facility in Florida, joined the company in 1965 working on Saturn V electrical systems. Since then he has managed Integration Electrical Systems and also Operations Engineering for IBM's portion of the Saturn/Apollo program. He began his Space Shuttle work in 1970 as manager of Shuttle Ground Systems Development in support of Phase B definition studies. Prior to being named to his current position, he was manager of LPS System Engineering. Mr. Satterfield's LPS endeavors have earned him several IBM awards and also the Public Service Award from NASA, for support of STS-1.



The Operational Control System for GPS

James J. Selfridge, manager of the IBM Federal Systems Division's GPS Los Angeles office, serves as liaison to the U.S. Air Force and associate prime contractors for GPS and supports the ongoing design and analysis tasks for GPS development. During the 1960s, he successively was manager of Advanced Air Defense in support of the SAGE System, responsible for IBM's Advanced Ballistic Missile Defense work with responsibility for contracts with the U.S. Army's Safeguard System Command and the Bell Telephone Laboratories, and developed a special data processing system for a classified program. In the mid-1970s, Mr. Selfridge was responsible for contracts with the Defense Communication Agency for the Worldwide Military Command and Control System's data processing systems and with the U.S. Army's Strategic Communications Agency for the Pentagon's Telecommunications Center. He shares a patent, awarded in 1962, for an error-detecting system for a digital computer. Mr. Selfridge joined IBM in 1949 after receiving a BSEE from Villanova University.



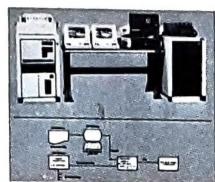
DSM: New Generation of Satellite Control

Kenneth J. Deahl is the Data System Modernization Technical and Staff Support Manager. Since joining IBM in 1960, Dr. Deahl has held a variety of program and advanced programs management positions. Included are program manager of AN/FPS-85 Phased Array Radar System Development on Large Aperture Seismic Array Program, manager of Software Development Measurement program, and participation in the MX Command and Control and Landsat D Image Processing System proposals. More recently, he was responsible for organization and management of the DSM early proposal activity. Dr. Deahl received his PhD in Physics from Carnegie-Mellon University in 1960 where he earlier received BS and MS degrees in Physics.



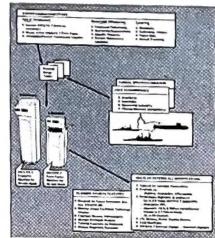
Thomas C. Wellington, an IBMer since 1966, has held various management and systems engineering/technical assignments in the IBM Federal Systems Division, including the manager of the hardware Systems Engineering group for the IGLOO WHITE project and also the System Design Manager of the TRIDENT Command and Control System Engineering and Integration program. Technical assignments have included various engineering development responsibilities related to Sonar Signal Processors, Sonar Displays, and the IBM Series/1 (MIL) computer. He is currently on the technical staff of DSM Systems Engineering. Prior to joining IBM, Mr. Wellington was associated with HRB-Singer and the Ordnance Research Laboratory of Pennsylvania State University where he earned a BS degree in Physics and an MS degree in Mathematics.

In the Previous Issue



MIL-STD-1750: The Air Force Approach to Computer Standardization

Many benefits are expected to accrue from this architecture; IBM's participation in the program is described.



The AN/UYK-43: A New Navy Standard Large Shipboard Computer

This is supporting the Navy's plan to sharply upgrade the functional capability, reliability and maintainability of the next-generation large shipboard standard computers.



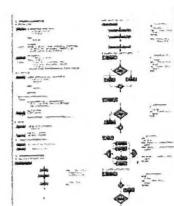
The AN/UYK-44: Militarized, Reconfigurable Processors/Computers for the Navy

Introduction of the AN/UYK-44 to the fleet will enable the Navy to improve small computer performance and reliability and to meet an increasing need for imbedded computers.



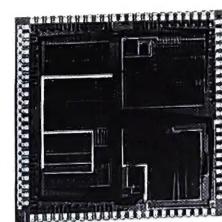
The Army's MIL-STD-1862 and the Military Computer Family

The Army's approach to computer standardization: a powerful architecture, extensive competition, and goals that anticipate major technology advances.



The Role of DoD's Ada in Software Standardization

IBM's Federal Systems Division is pursuing software standardization through the use of DoD's Ada language, and an Ada-based software design language.



LSI Applications in Military Systems

The powerful building block approach of IBM's Advanced Development Program master image methodology is being used in its first application—the associative comparator.

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